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COMPARATIVE ANALYSIS OF HUMAN ELBOW FLEXION CAPABILITY AND NAUTILUS ELBOW FLEXION MACHINE RESISTANCE PATTERNS

by

LINDA J. ROBINSON-EDWIN

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF PHYSICAL THERAPY

EDMONTON, ALBERTA

Fall 1987

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled COMPARATIVE ANALYSIS OF HUMAN ELBOW FLEXION CAPABILITY AND NAUTILUS ELBOW FLEXION MACHINE RESISTANCE PATTERNS submitted by LINDA J. ROBINSON-EDWIN in partial fulfillment of the requirements for the degree of Master of Science.

Skumar
Supervisor

H Chl.

W Vargo

E W Bedingfield

Date: October 9, 1987

DEDICATION

To Nash and Djolani Nneka, also symbols of dreams come true and dreams yet to be fulfilled.

ABSTRACT

The manufacturers of Nautilus equipment claim that superior strength gains can be achieved using their equipment. The basis for this claim has not been substantiated though the company has suggested that this is due to ideal matching between muscle capability patterns and the resistance patterns of their machines.

The purpose of this study was i) to determine and describe the elbow flexion capability pattern (EFCP) with respect to the body position assumed while performing on the Nautilus elbow flexion machine (NEFM); ii) to determine and describe the pattern of resistance provided by the NEFM; iii) to compare the NEFM resistance pattern with the EFCP; iv) to determine and describe the components of NEFM resistance and their contribution to resistance torque pattern.

To determine the EFCP, subjects were young, healthy women (n = 25). Isokinetic torque and joint angle were measured using a Cybex dynamometer. %max torque-joint angle curves were determined.

To determine the NEFM resistance pattern, two methods were used. The first method was based on analysis of a constant velocity, friction-free model of the components of NEFM resistance. Principles of static mechanics were applied. The second method involved the use of a trained subject who moved the NEFM at approximately constant velocity. Strain gauges recorded the torque variability. Machine lever arm angle was monitored using an electrogoniometer. In both cases, %max torque-lever arm angle curves were determined for different loads. Comparisons of these curves showed how performance variables

might interact with the inherent NEFM resistance pattern to produce differences between actual and predicted resistance.

The main conclusions were:

i) the EFCP is an ascending-descending curve;

ii) the NEFM resistance based on the mathematical model is a linear curve independent of load;

iii) the NEFM resistance based on a single subject's performance on the machine is a series of linear curves of decreasing slope as load is increased;

iv) there is a less than ideal match between the EFCP and NEFM resistance pattern;

v) the individual components of NEFM resistance could be modified to improve the match between resistance and EFCP.

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LIST OF SYMBOLS AND ABBREVIATIONS

NEFM	Nautilus elbow flexion machine
EFCP	elbow flexion capability pattern
EAA	effort application arm
kg	kilogram
cm	centimetre
°	angular degrees
$°s^{-1}$	degrees per second
ft lb	foot pound
min	minutes
MVC	maximal voluntary contraction
%	percent
%max	percent of maximal value recorded
α	Greek letter 'alpha'
ß	Greek letter 'beta'
sin	sine
cos	cosine
C	chain
F	force on C
E	effort
A	application arm of a specified force
W	weight
WA	weight arm
L	true lever arm
N	Nautilus elbow flexion machine cam

CHAPTER I

INTRODUCTION

Rationale

The recent surge of interest in general health and fitness has brought with it an increased interest in specific strength training. As a result, a number of muscle strengthening machines have been, and continue to be, introduced to the strength training market. Several companies aim to produce the 'ideal' machine, this being one that maximizes strength gains by providing a sufficiently high strength stimulus to all points in a muscle group's range of motion. Theoretically, this may be achieved through the matching of resistance patterns to muscle capability curves throughout the entire range of a selected movement. As one manufacturer put it,

> Automatically variable resistance is an absolute requirement for high intensity exercise . . . . Since movement produces changes in usable strength, it is necessary for the resistance to vary in proportion to the resulting changes in strength . . . [1]

The Nautilus Company manufactures equipment which, it claims, is superior to more traditional weight training equipment - e.g. barbells - because of accurate matching of the machines' resistance patterns with patterns of muscle group capability. The equipment is said to isolate various muscle groups and subject them to variable maximal resistance, accommodating their specific strength curves.[2] A review of the Nautilus Sports/Medical Industries literature suggests that the company has had remarkable success in marketing their equipment. The first machine was manufactured in 1948, was modified several times, and

subsequently introduced to the market in 1970.[3] Today, there are 37 different machines available for strengthening various muscle groups.[4,5] The effectiveness of Nautilus equipment in increasing muscle strength has been demonstrated by Company research.[4,6,7] However, the superior strength gains expected as a result of ideal matching has not been shown to be the case.

The findings of the Colorado Experiment,[6] published in 1974, showed that significant and dramatic increases in muscle mass and strength could be achieved over a relatively short time period using Nautilus weight training equipment. The selected sample of one college age male athlete and one other male, the designer of the equipment, suggest that motivational factors may have played a significant role in influencing the outcome of the study. A second study, the findings of which were published in 1974,[7] again demonstrated the effectiveness of Nautilus weight training equipment in increasing muscle strength. In this case a larger, more random sample was used. Extensive testing showed significant increases in both muscle mass and strength, as well as improvements in the subjects' ability to perform a number of functional tests. However, both studies failed to compare Nautilus equipment with other forms of strength training equipment. The claim of superiority has therefore not been substantiated by the Nautilus Company's research. In fact, comparisons made with other forms of equipment, have shown Nautilus machines to be equally effective, but not superior, in producing muscular strength gains.[8,9]

A comparison of the relative effectiveness of Nautilus apparatus versus Universal Gym equipment was carried out using 60 male

volunteers, aged 20.8 ± 1.4 years. These physical education students were divided into two groups. Both groups carried out similar general strength training programs for a period of ten weeks. They were then tested on Universal Gym equipment. Both groups showed significant strength increases though neither was superior.[8] The interpretation of these findings is made difficult by the fact that the training programs were not exactly the same. However, they were considered equivalent. The training protocols used were those recommended by the manufacturers and resulted in the Universal Gym group performing two sets of repetitions at 10 repetition maximum (RM) and 8 RM each, while the Nautilus group performed one set of 10 - 12 RM. The actual loads lifted by each group were not reported. The Universal Gym group had the advantage of familiarity with the test equipment and thus would have been expected to show greater strength gains than the Nautilus group. The fact that both groups were equal suggests that the performance of the Nautilus group may have been superior. However, this could not be assessed since the relative intensity of training of the groups was not determined.

A comparison of the responses of college age males to training using Nautilus machines versus traditional barbells involved 22 subjects who trained over a five-week period. The objective was to increase dynamic strength of the elbow extensors and shoulder flexors. The training programs were similar and the training protocols the same. A 6 RM was used in both cases with resistance being progressively increased on a weekly basis. The subjects were tested on 3-minute rhythmic isometric contractions of the elbow extensors and

shoulder flexors. The static test as an indicator of dynamic strength may not have been the most suitable, but since the same test was used on both groups, this ensured validity and avoided the problem of familiarity with testing equipment. Both groups showed increased strength but there was no difference in the strength gains that were achieved as a result of using either type of equipment.[9]

The comparison of strength gained using Nautilus versus other types of equipment is only one approach to assessing the relative efficiency of these machines. A second approach is to look directly at resistance patterns and to compare these with muscle capability curves. The resistance patterns of several pieces of Nautilus training equipment have been studied in order to assess the extent of matching that exists between resistance and muscle capability patterns.[10,11] In general it has been found that the resistance and capability curves bear no similarity to each other. One study,[10] available only in abstract form, used slide images as a basis to construct fibreboard models of the essential components of five different Nautilus machines. Resistive torque patterns were found to depend mainly on the effective lever arm of the cam, this being the perpendicular distance from the weight chain to the cam pivot point, at different positions throughout the range of motion. The machine resistive torque was normalised to percentage maximum and compared to computer-generated graphics of similarly normalised human torque capability patterns. None of the pairs of curves was precisely matched and the extent of the differences varied for each pair of curves and at different points along selected pairs of curves.[10] From the brief write up of this

study, it is not clear how or whether the human torque capability curves were determined. Thus the basis for comparison is not clearly established and cannot be fully assessed.

A study of the Nautilus leg extension machine[11] compared the machine resistive torque measured by strain gauges mounted on a cybernetic arm with human torque capability measured isokinetically at various speeds. The patterns were clearly dissimilar in shape, and the extent of mismatching varied at different points along the curves.

Thus neither of the Nautilus Company's claims of superior strength gains nor matching resistance patterns have been substantiated by independent researchers. Detailed analysis has been made available regarding the resistance pattern of the leg extension machine but there is a lack of detailed information on other Nautilus machines. This study provides a detailed analysis and comparison of the resistance pattern of the Nautilus elbow flexion machine with the human capability pattern for elbow flexion.

A basic problem with regard to comparing resistance and capability curves lies in the description of a capability curve. There is obvious discrepancy between the Nautilus Company's description of the strength capability curve of muscle[12] (Figure 1) and that described in the literature for both isolated muscle[13-17] (Figure 2) and the elbow flexors [18-25] (Figure 3). The Nautilus literature describes an ascending curve whereas in vivo and in vitro studies of isolated muscle as well as studies of the elbow flexors under different conditions have yielded ascending-descending curves. Various authors have shown elbow flexor torque curves to vary with subject

Figure 1

The Nautilus Strength Curve of Muscle

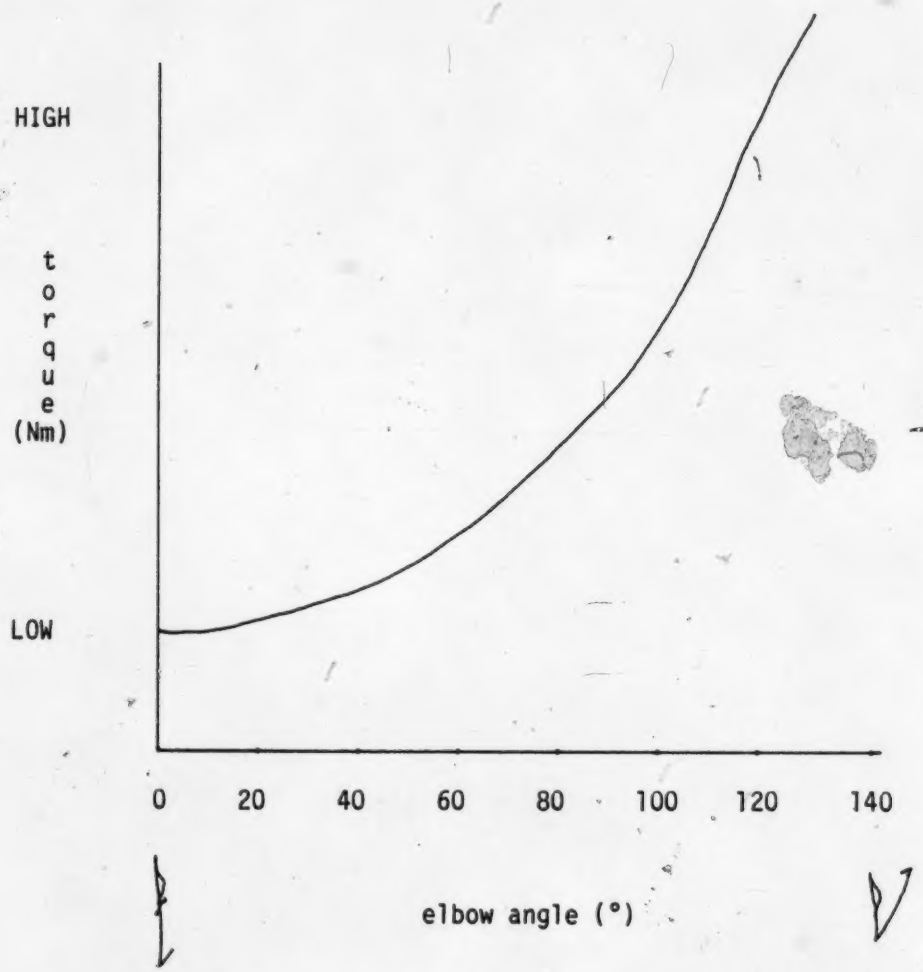


Figure 2

Muscle Length-Tension Relationship

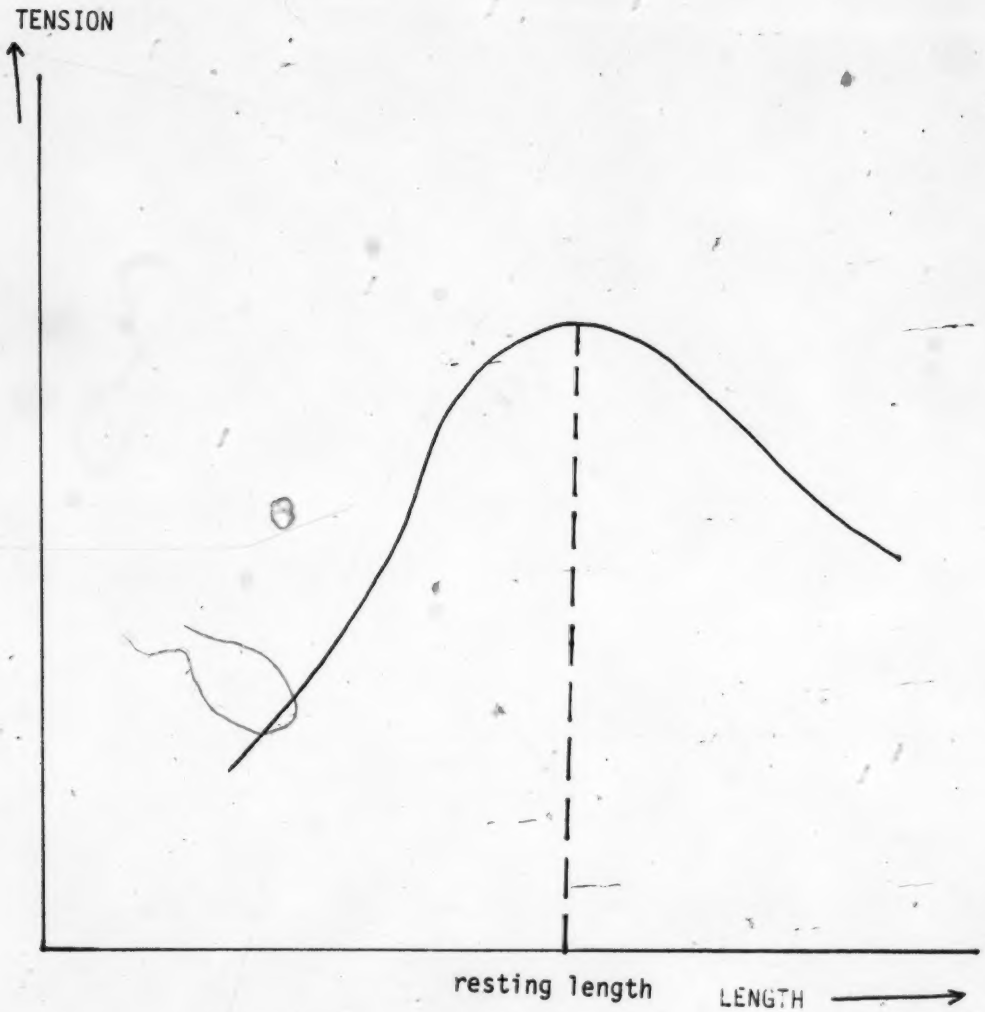
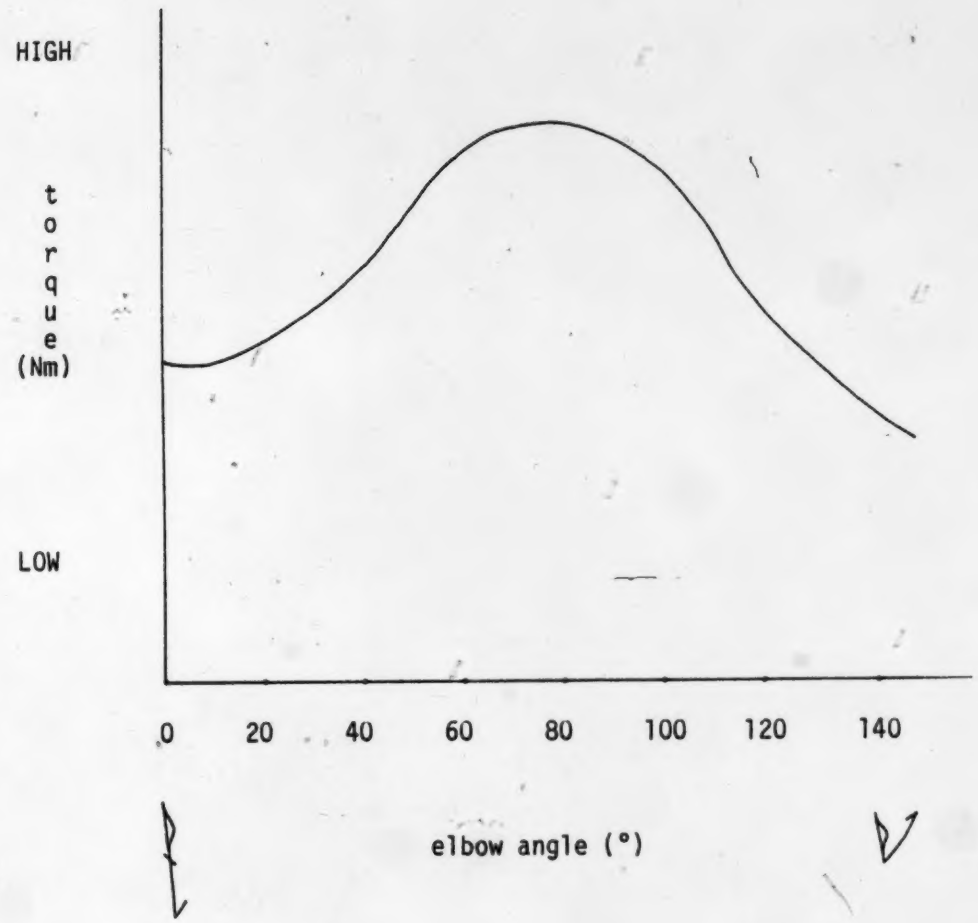


Figure 3

Generalized Strength Curve of Elbow Flexors



posture[20,26,27] and positioning of adjacent joints and/or segments.[20,25,28-30] In this study the torque-angle curve of the elbow flexors was derived on the basis of the standard body position for use of the Nautilus elbow flexion machine so that valid comparisons could be made between capability and resistance patterns.

Objectives of the Study

The major objectives of the study were as follows:

1. To determine and describe the elbow flexion capability pattern (EFCP) i) with respect to a standard body position, i.e., the position for use of the Nautilus elbow flexion machine (NEFM), and ii) under conditions of constant velocity.
2. To determine and describe the pattern of resistance provided by the NEFM under conditions of constant velocity.
3. To compare the NEFM resistance pattern with the EFCP in order to determine the extent of matching of the curves.
4. To determine and describe the effect of each of the resistance components of the NEFM and to examine how each contributes to the overall resistance torque.

Significance of the Study

By determining the pattern of resistance provided by the NEFM as well as the various resistance components' contributions to the overall resistance, an understanding is provided of the way in which the machine works. Describing the EFCP enables comparisons between normal muscle capabilities and NEFM resistance and gives some indication of the possible role of the NEFM in rehabilitating muscles to normal

strength. The company claim of perfect matching could be more closely investigated.

The findings of this study would be relevant to all types of personnel who might consider using the NEFM for rehabilitation and/or training. On the basis of a scientific investigation, greater objectivity is allowed in the selection of the most appropriate training tool so that rehabilitation methods can be matched to specific patterns of strength requirements. Comparisons can also be made between the EFCP and the resistance patterns of other more traditional forms of equipment that may be modified and used in the standard position for use of the NEFM.

Research Hypothesis

There will be differences between the EFCP and the NEFM resistance pattern.

Delimitations

1. The NEFM resistance pattern determined was restricted to a single machine, the elbow flexion component of the Nautilus Biceps/Triceps Plate Loading Machine.*
2. The EFCP determination was limited to constant velocity movement performed at two speeds, $60°s^{-1}$ and $90°s^{-1}$.
3. The EFCP determination was limited to 25 female subjects ranging in age from 19 to 29 years, in weight from 40.0 to 76.3 kg. and

---

* Nautilus Sports/Medical Industries Inc.,
151 East Ohio Avenue, Lake Helen,
Florida 32744, U.S.A.

in height from 152.2 to 178.1 cm. These were all normal subjects with no history of systemic or significant upper limb pathology.

Limitations

1. Subject selection was made on a volunteer basis and did not constitute a random sample. Subjects were randomly assigned the order of speed of testing. A selection of a sample of young, healthy females means that the findings of this study cannot be generalised beyond a similar population.
2. The EFCP determination and NEFM analysis were based on a constant velocity condition. These isokinetic movements are fairly artificial in that they are atypical of movements that occur in everyday life. When performance is not constrained, muscles usually shorten and lengthen at various rates. However, the constant velocity condition was useful for testing under standardised conditions and for simplifying the mathematical analysis.
3. This investigation did not account for individual variations in elbow angle for different positions of the effort application arm. However, the torque developed was related to the position of the effort application arm for both the resistance and capability patterns, and the assumption made that with proper alignment of the elbow joint axis with the effort application arm axis the elbow angle would be altered in a similar fashion on both machines.
4. This investigation did not take into account the possibility of

variations in individual performance on the NEFM. Instead, emphasis was placed on the inherent capability of the NEFM to provide resistance.

Operational Definitions

1. Elbow flexion capability pattern - the isokinetic strength curve of elbow flexion performed at selected speeds of $60°s^{-1}$ and $90°s^{-1}$ and in a standard body position; the relative torque developed is plotted against the corresponding angle of the effort application arm.
2. Nautilus elbow flexion machine resistance pattern - the resistance provided by the loaded machine: i) as measured in arbitrary units of strain applied to move the effort application arm or, ii) as calculated on the basis of a mathematical model of the resistance system; the relative resistance torque is plotted against the corresponding angle of the effort application arm.
3. Slow speed - $60°s^{-1}$ angular velocity of movement of the Cybex II^{+} isokinetic dynamometer during elbow flexion.
4. Fast speed - $90°s^{-1}$ angular velocity of movement of the Cybex II^{+} isokinetic dynamometer during elbow flexion.

Note: Both slow and fast speeds represent very slow speeds compared to those that occur in activities of daily living and with specific sports.[24] The speeds are differentiated here merely to facilitate discussion.

5. Elbow flexion - movement of the elbow joint from a position of full extension (0°) into maximal flexion; movement performed with

hands gripping bar and wrists maintained voluntarily in a mid-flexed position.

CHAPTER II

REVIEW OF THE LITERATURE

Static Elbow Flexor Curves

The earliest literature on strength curves of the elbow flexors appeared in the work of authors concerned with developing a more objective approach to strength assessment. In the field of physical medicine, muscle weakness had long been recognised as an important factor characterising neuromuscular disease.[18] On the basis of a finding of weakness, important decisions are made regarding the selection of appropriate medical intervention and/or the implementation of specific strengthening programs. The importance of obtaining reliable and detailed information about muscular strength led to the early attempts to describe maximum muscle capability with respect to an entire range of joint motion. The quantification of muscle force was undertaken in an extensive series of studies using cable tensiometry to measure the forces developed by groups of muscles acting at various joints.[18,19,20] The major objective of this work was to determine the optimum joint angle for force development. An important offshoot of this work was the description of the force capability, at selected joints, as a function of joint angle. These early strength curves were strictly isometric.

Isometric tests of the elbow flexors have been carried out under different conditions of whole body and body segment positioning, fixation and stabilisation.[18-25] The basic methodology of these studies, including subject characteristics and units of measurement have been summarised in Table II-1. Male and female subjects have been

tested in standing, supine and sitting positions. A comparison of the isometric force exerted about the elbow joint in standing versus that in sitting found that the greater mean torque was generated in the sitting position.[26] The positioning of the forearm in supination, pronation and midpronation-supination during elbow flexion has also been studied.[20,28,29,30] In general, the midposition has been found to be the most efficient in terms of force production. The literature also suggests that supination of the forearm produces a higher elbow flexion force than that produced when the forearm is pronated.[28,30] Although no studies have attempted to isolate the effect of shoulder positioning on elbow muscle force development, it has been suggested that extension at the shoulder joint might enhance the function of the biceps brachii in elbow flexion.[20]

In most testing, isolation of the elbow flexors has been attempted by application of the resistance cuff or pad just proximal to the wrist. In some studies, the subjects grasped a handle[22,29] thereby increasing the possibility of performing a multi-joint movement, including elbow and wrist flexion, to enhance force development. When the effects of grasping at the hand instead of proximal to the wrist were compared, no significant differences were found in terms of force development.[29] Various forms of stabilisation have been used. In sitting and standing, the feet are generally placed flat on the floor.[21-24] In several studies, footboards were placed against the feet of supine subjects.[18,20,28] Footboards have been found to significantly increase elbow flexor force output.[18,20]

There is lack of agreement in the literature on the appropriate

Table II-1 Static Elbow Flexor Curves

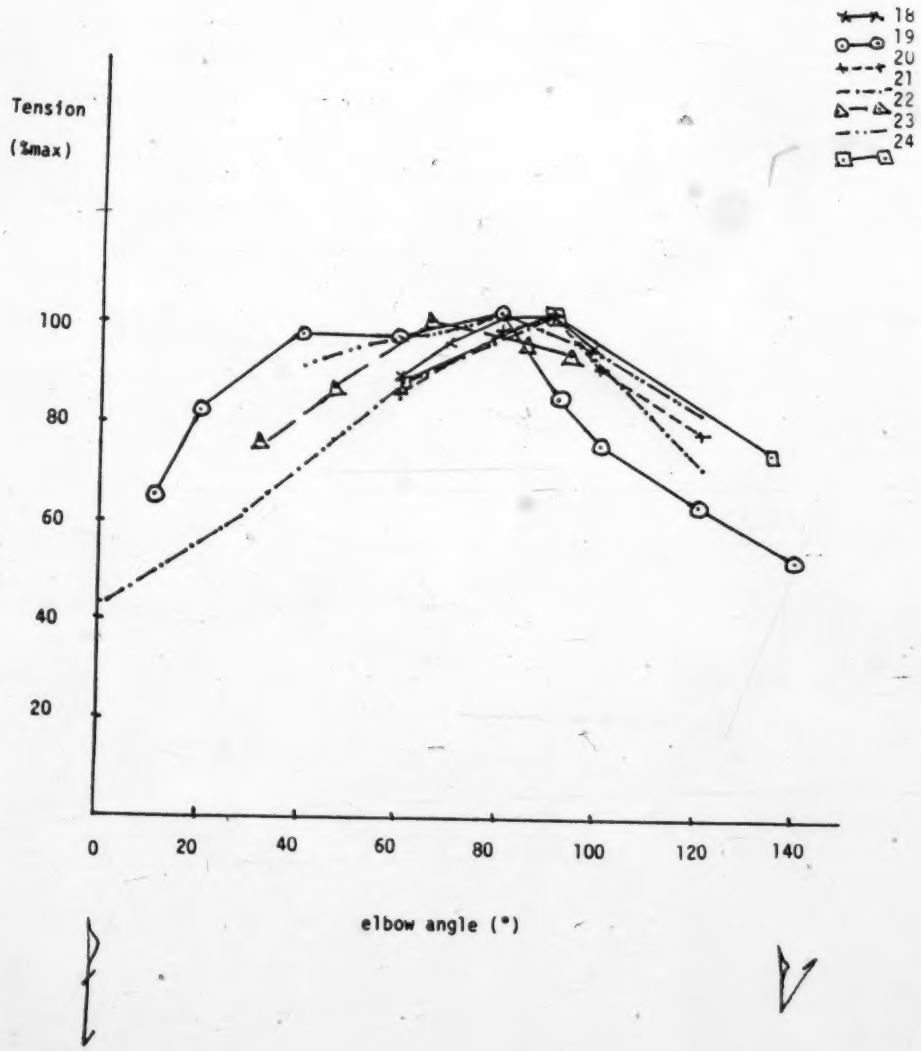
Author(s)	Body Position	Shoulder Position	Forearm Position	Subject Age	Subject Sex	Subject Occupation	Measuring Tool
Wakim et al., 1950[18]	supine; flat	adducted; neutral	supinated	young adult	20 F 4 M	-	cable tensiometer
Clarke et al., 1950[19]	supine; hips and knees flexed	adducted	midposition	young adult	64 M	college men	cable tensiometer
Elkins et al., 1951[20]	supine; flat	adducted; neutral	midposition; pronated; supinated	young adult	9 F 9 M	-	cable tensiometer
Williams & Stutzman, 1959[21]	standing	adducted; neutral	midposition	young adult	10 M	college men	cable tensiometer
Doss & Karpovich, 1965[22]	standing	adducted; neutral	-	19-23 yrs.	37 M	junior college men	special dynamometer
Singh & Karpovich, 1966[23]	sitting	adducted; shoulder yokes	supinated	20-25 yrs.	20 M	P Ed students	special dynamometer
Jorgensen & Bankov, 1971[24]	sitting	adducted; neutral	supinated; pronated	30, 37 & 41 yrs.	3 M	-	strain gauge dynamometer
Knapik et al., 1983[25]	sitting	adducted; neutral	midposition	26.1±3.8 24.9±4.1	16 M 15 F	mostly soldiers	modified isokinetic dynamometer

units for measurement of muscle tension. This leads to difficulty in the direct comparison, interpretation and use of the derived strength curves. Some authors plotted the resistive force that was applied perpendicular to the distal joint segment at an arbitrary distance from the joint, e.g., just proximal to the wrist;[19,21,23,24,25] others, at a specific distance from the joint.[18,20] Because of the known interaction of force and distance in the production of torque (T =F x d), other authors have recorded units of torque.[24,25] The lack of a standardised experimental protocol has resulted in varying definitions of the 0° position of the elbow, i.e. full flexion or full extension. Also, in some cases, joint angle has been set before the initiation of contraction while in other cases joint angle was determined, perhaps more accurately, during maximal contraction.[20] Despite these variations in technique, the typical isometric elbow flexor strength curve is an ascending-descending curve. Where possible, raw data have been extrapolated from the text, joint angle converted to a standard of 0° at full extension and muscle capability at each angle represented as a percentage of the maximum value. The resultant percent maximum (%max) values have been plotted against joint angle to give a series of strength curves (Figure 4). The angle of peak tension development was found to vary between 65° and 90° of elbow flexion, occurring most commonly at 90°.[18,20,21,24]

The main factors which determine the shape of the isometric elbow flexor strength curve may be classified as inherent or as external in relation to the elements of the contractile unit. The length-tension relationship of muscle is an inherent feature[32,33] modified by the

Figure 4

Static Elbow Flexor Strength Curves



effects of biomechanical factors (external) that affect the muscle in situ,[32,33] and neural (inherent) and psychological factors (external) that limit force development under varying circumstances.[33-35]

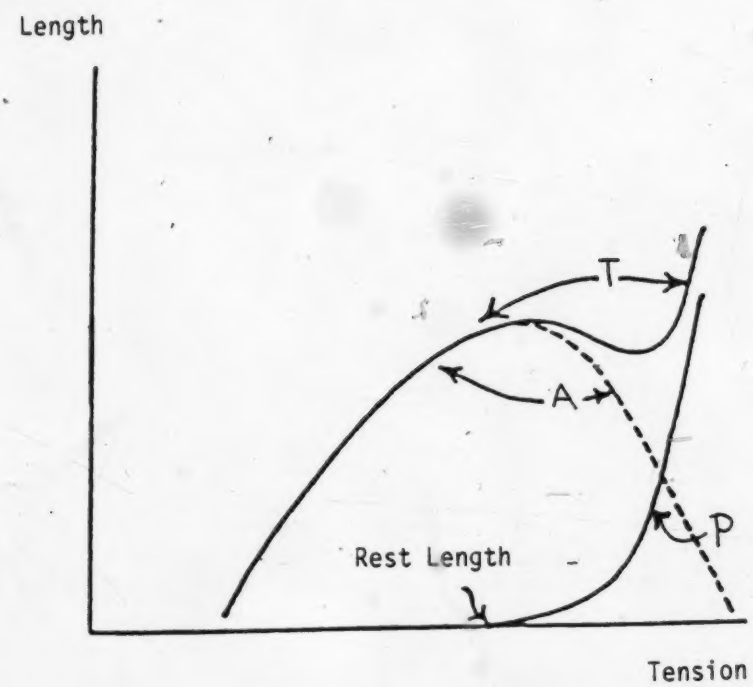
The Length-tension Relationship

Muscles exist in the body as tension generators. Under normal conditions, various factors limit the ability of a muscle to develop tension. The limitation of force development in relation to its length is an inherent characteristic of muscle. Early descriptions of the length-tension relationship were provided in the work of several authors.[13,14,15] This fundamental property of muscle was first described on the basis of studies of whole frog muscle.[13] The tetanically stimulated muscle was contracted over a range of lengths and was found to generate varying tensions at each length, both at rest and during contraction. The resting tension was determined at the various lengths and provided the passive length-tension curve. When subtracted from the total tension generated at each length this yielded the curve of active tension (Figure 5). The curve of active tension was shown to be a fairly symmetrical ascending-descending curve, with maximal developed tension occurring at or near the resting length.[13] The resting length was taken to be that where the muscle was just taut between its supports.

The active length-tension relationship first described for frog muscle, was later identified as being similar for isolated single muscle fibres, with maximum tension occurring at resting length and decreasing almost linearly to zero at 200% resting length.[14,15] When

Figure 5

Length-Tension Curve of Frog Muscle



A = Active tension of stimulated muscle

P = Passive tension of unstimulated muscle

T = Total tension of stimulated muscle

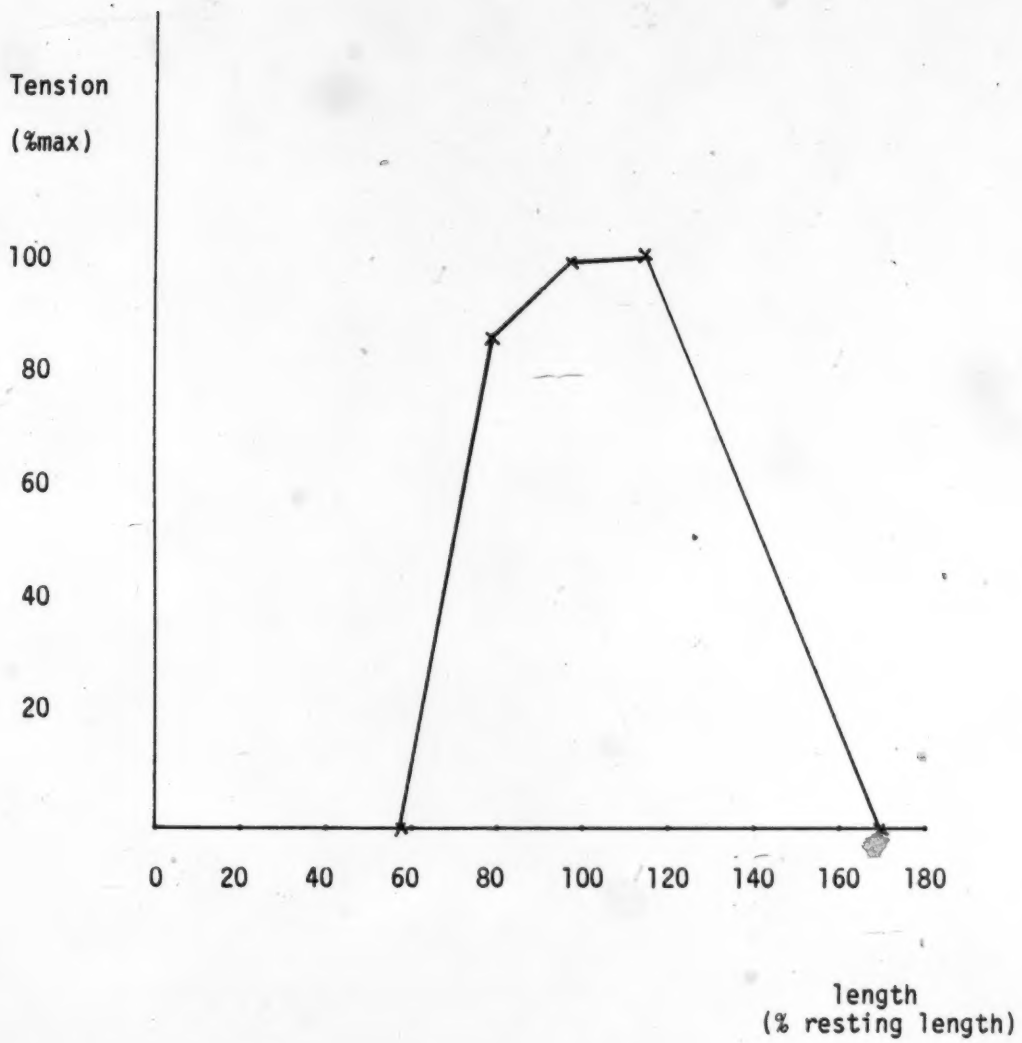
special precautions were taken to ensure uniformity of sarcomere length within the part of the fibre being studied, the length-tension was found to plateau between 94% and 106% resting length; to decline more rapidly to zero at 172% resting length and to increase more rapidly up to the plateau at sarcomere lengths between 79% and 94% resting length[15] (Figure 6). The shape of this length-tension curve is thus generally consistent with the active tension curve of the previous author.[13] Further support is provided in the fact that the events of the length-tension curve of muscle fibre can be related to the critical events of shortening as described by the sliding filament theory and can therefore be explained on the basis of this theory.[15,36,37,38] It is generally agreed that muscles exert maximum force at or near resting length while extreme shortening and lengthening produce a decrease of tension. The tension generated is proportional to the number of attached crossbridges with equal tension being generated at each crossbridge.[36]

In a study of human subjects where the muscles tested were essentially free of any bony attachments, it was possible to clearly show the variation of tension with muscle length.[17] The length-tension curve was again shown to be similar to that of frog or toad sartorius.[13,16]

Bony attachments normally serve as limiting factors both to the actual length of a muscle within the body and to the range of lengths which the muscle may assume. One study examined the relation between elbow angle and isometric tension in voluntary isometric contractions.[39] The hypothesis presented was that sufficiently large

Figure 6

Length-Tension Curve of Muscle Fibre



changes in muscle length occur during elbow flexion so that the complete length-tension relationship could exist within the working range of motion. The study concluded that the tension in all the elbow flexors together shows an almost complete isometric length-tension curve. Elbow flexion in this case was performed with the forearm in the midprone position and through a range of motion of 30-140°, where 0° was taken to be the fully extended position. No explanation was provided for not assessing the first 30° of movement which may have represented the missing portion of the curve.

Biomechanical Factors in Elbow Flexion

The strength curve of a muscle group represents a modification of the unique length-tension effect by biomechanical factors related to the fixed attachments of muscles to bony points. These bony points change their relationship to each other as a joint is taken through its range of motion about a given axis. The elbow joint is one where a wide range of motion is allowed. Classified as a trochoginglymoid joint, it permits hinge motion in one plane and axial rotation in another.[40] Flexion/extension occurs at the humeroulnar articulation in various combinations with pronation/supination at the radioulnar ariculation.[40] When axial rotation is limited by fixing the forearm in supination, flexion at the elbow may be accompanied by inward rotation at the glenohumeral joint.[40]

The flexion/extension axis of the elbow joint has been investigated.[41,42,43] Most authors have found a moving instantaneous centre of rotation,[42,43] but only one author found significant

movement.[42] The elbow joint is therefore considered to be essentially a hinge joint with elbow flexion occurring in a circular arc about an axis at the centre of the trochlea and capitulum.[44] The axis of motion is not influenced by the degree of pronation or supination of the forearm. The range of motion available in pure flexion/ extension is about 145° from a fully extended position, although the available movement is greater in females.[45] The approximately 15°-20° of hyperextension available at the elbow joint increases the range of motion in females to 160-165°.

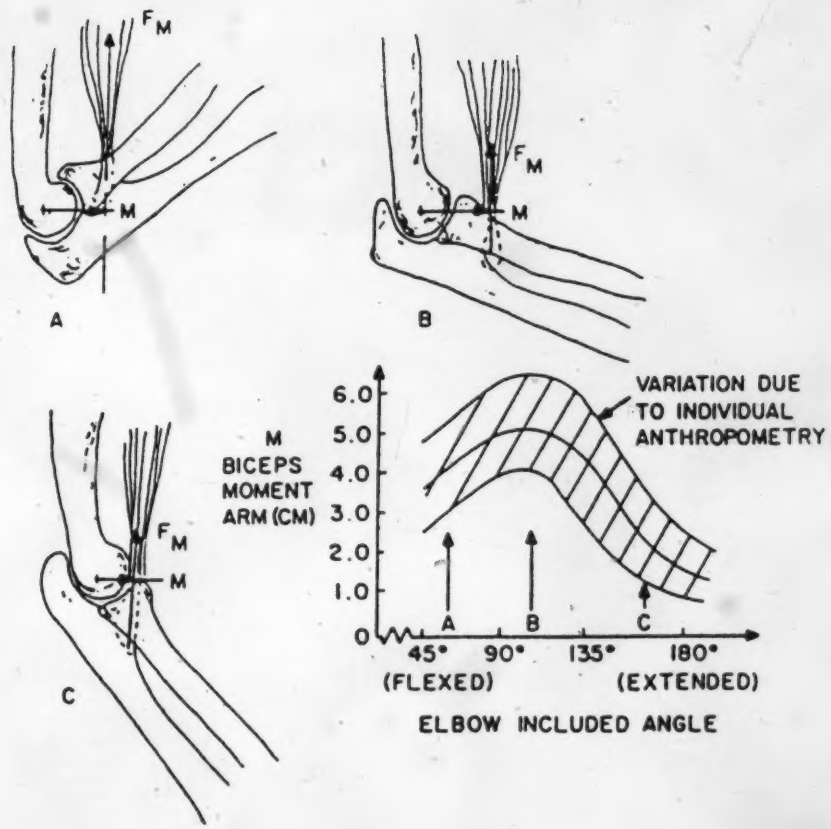
In allowing movement through such a wide range of motion several muscles act together. The brachialis and biceps brachii are considered to be the principal flexors; brachioradialis, extensor carpi radialis longus and the pronator teres are auxiliary flexors.[46-48]

These muscles produce elbow flexion by exerting forces at their attachments distal to the elbow joint. While the available force varies with the length of the muscle, the rotatory component of the force generated at each joint angle depends on the length of the effective moment arm. The effective moment arm, or perpendicular distance from the axis of rotation to the line of pull of the muscle, varies and is directly dependent on the angle of insertion of the muscle with the bone (Figure 7). The angle of insertion is not constant but varies in a consistent pattern throughout a selected movement. The actual moment generated therefore depends on the interaction between force capability and the biomechanical moment arm of the muscle.

The effective moment arm of the biceps brachii has been

Figure 7

Angle-of-Pull Effect



determined for different elbow angles under the assumption that the muscles fibres run parallel to the upper arm.[39,49] The moment arm has been shown to vary throughout the movement of elbow flexion, being maximal at the 90° elbow position. However, the assumption of parallelity of the biceps muscle fibres has been shown to be less than accurate. In vitro measurements of the true elbow flexor moment arms have been undertaken.[48,50] The moment arms of the elbow flexors, at different elbow angles and with the forearm supinated, have been determined by a serial sectioning method.[48] It was found that the moment arms of all the elbow flexors increase progressively between 0° and 100° flexion being almost twice the value in the flexed position of that in the extended position (Table II-2).These findings suggest that the changing moment arms play a significant role in modifying the effect of tension generated within the elbow flexors during movement.

Neural and Psychological Factors

Maximum tension has been defined as "that isometric tension set up when the greatest number of fibres contract which it is possible to stimulate simultaneously by voluntary innervation".[51] The arrangement of muscle fibres into groups or motor units supplied by a single nerve, is one pathway through which neural factors infuence tension development. The activation of motor nerve fibres determines the rate of tension development, the amount of tension developed and the period of time for which tension is maintained.[52] Motor unit recruitment is the major mechanism involved in the gradation of muscle contraction.[53]

Table II-2 Potential Moments of Elbow Flexors[48]

Muscle	Elbow extended with forearm supinated				Elbow flexed 100° with forearm supinated			
	Moment arm (cm)	PCSA	Potential moment	% total moment	Moment arm (cm)	PCSA	Potential moment	% total moment
Biceps	1.96	2.3	4.51	25.83	3.20	2.3	7.36	19.47
Brachialis	0.87	7.0	6.09	34.88	1.98	7.0	13.86	36.68
Brachioradialis	2.56	1.5	3.84	21.99	5.19	1.5	7.78	20.59
Extensor carpi radialis	1.16	2.6	3.02	17.30	3.38	2.6	8.79	23.26
Total moment			17.46				37.79	

PCSA - physiological cross-sectional area
Potential moment - moment arm x PCSA

Two major types of motor fibres have been identified. Type I fibres have a long firing frequency which is generally achieved early in the time course of a maximal contraction, and is then maintained for a relatively long period. Type II fibres have a high firing frequency which will increase until the muscle develops maximum tension. These fibres however, fatigue rapidly.[54] The size principle suggests that the smaller, Type I fibres are generally preferentially recruited at the start of contraction with the larger fibres being recruited later as increased tension is required.[52,53] However, this preset bias is variable and recruitment patterns may vary not only from movement to movement[52] but also within a given movement.[54-57] In fact, human muscles have been shown to have equal tension developing capabilities in fast and slow muscle fibres[58] which suggests a possible complex interaction between tension requirements and fatigue factors in the recruitment of motor units.

The normal pattern of motor unit firing is asynchronous.[55] The synchronisation of firing of motor units can lead to increased tension development in that, according to the all-or-none principle, the larger the amount of motor units activated, the greater will be their summed tension.[55-57] However, maximum innervation of motor units does not always mean that the maximum tension is developed. This is due to the fatigue factor.[51] In order that a contraction be maintained for longer than about 0.1 second, it is necessary that the first set of fibres is soon exchanged for a second set and so on. It has been suggested that before activating the muscle, the subject takes a view of the work to be done with regard to effort and time, and then

recruits motor units in a regulated manner so as to accomplish the specific task.[51] The central nervous system thus decides the most appropriate recruitment pattern and modifies output by varying the number and type of motor units recruited.[52]

The concept of maximum innervation is subject to the condition of being voluntary. It is also possible through pathways of voluntary control to limit the tension developed within a muscle. In an early study,[59] it was shown that the strength gains observed after four weeks of training to perform hand curls were due primarily to the will of subjects to perform a maximum effort. Studies of motivational factors show clearly that psychological factors caused significant variability in the strength responses of a single individual.[34,35] The finding that individuals could generate significantly more elbow flexor tension if given the suggestion of strength under hypnosis shows that human strength is limited by psychologically induced inhibitions.[34] These inhibitions may be reduced by the use of vocal commands.[35]

The Force-velocity Relationship

The isometric tension that can be developed in a muscle is largely a function of muscle fibre length and is an inherent characteristic of muscle. Isometric tension represents the maximum potential of a muscle, or muscle group, to generate force, given unlimited time. During dynamic contractions, a muscle may not have time to develop its full tension potential at any given length as length varies at a speed governed by the speed of movement.[60] The

mechanical changes observed in muscle occur as a result of chemical reactions which proceed at a more or less fixed rate.[61] This suggests that there must be a minimum time requirement for maximum force development. If this requirement is not met, then the tension generated will be submaximal and directly related to the speed of movement.[62]

The force-velocity curve for intact muscle shows an inverse relationship between force developed and speed of movement during concentric contraction.[63] Muscles in the body tend to follow a fixed force-velocity relationship that is partly dependent on the inertia of the load lifted, and mainly dependent on the inherent characteristics of muscle.[63,64] That the force-velocity curve is a function of the length-tension relationship has been clearly shown.[65,66] Length-tension curves have also been reproduced on the basis of the force-velocity characteristics of muscle.[66] The tension developed during a dynamic contraction is therefore linked to the rate at which crossbridges can be formed, broken and reformed.

In a study of the torque developed by the elbow flexors under dynamic, constant velocity conditions, the force-velocity curves derived were similar to those of previous authors.[24] However, the rate of change of length in the biceps brachii has been found to vary during constant angular velocity joint movement.[67] When the velocity of shortening of the biceps brachii was held constant through the use of a specially constructed dynamometer, curves following the trend of the force-velocity relationship were again observed.[67]

The force-velocity relationship therefore significantly affects

the torque which may be developed during dynamic activity. This property of muscle must be taken into consideration when attempting to describe strength curves.

Dynamic Elbow Flexor Curves

The standard length-tension diagram, like the standard length curve of muscle, is derived from a series of static measures, each taken at a different muscle length or joint position. These diagrams, being static, do not represent those factors which influence the dynamics of moving continuously from one point to another. The temptation to ascribe dynamic properties to these curves should be avoided as it is not likely that equivalent curves would be derived. In an effort to describe the maximal muscular capability during dynamic motion, several authors have derived dynamic elbow flexor strength curves, both in uncontrolled concentric conditions[22,23,25] and in velocity controlled concentric conditions.[25]

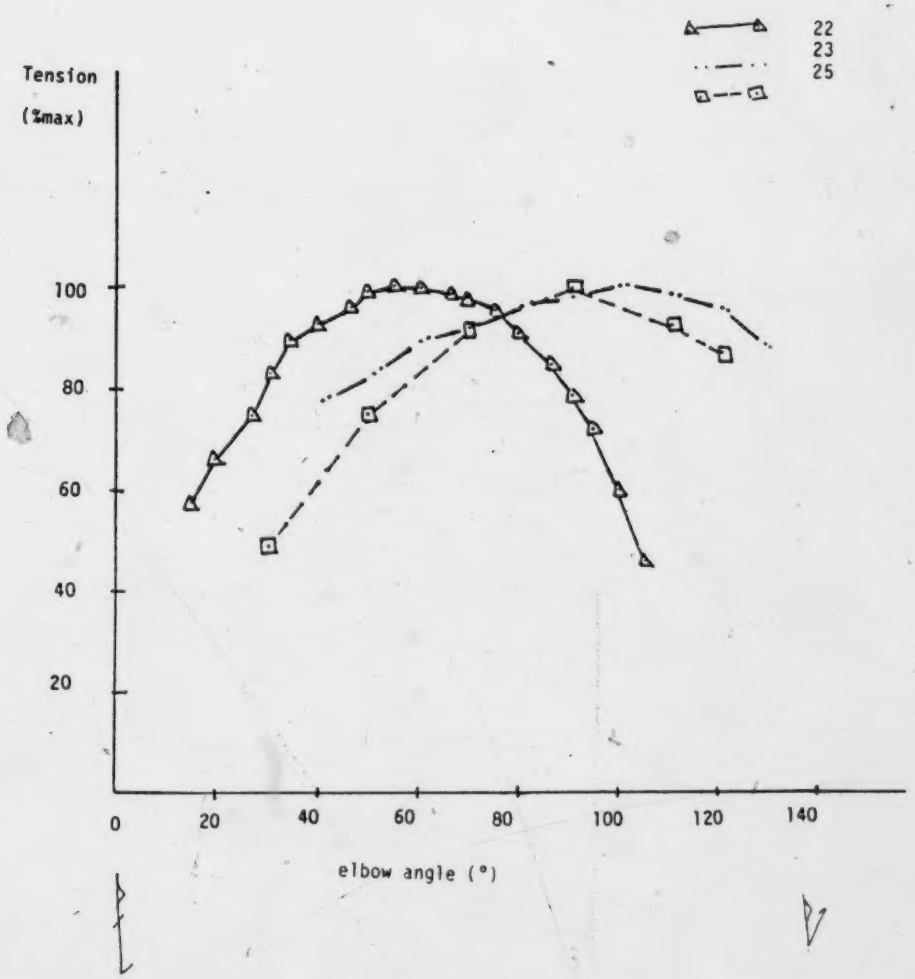
Few attempts have been made to describe strength during uncontrolled concentric movements due to the difficulty of devising appropriate test equipment. Using a specially constructed dynamometer concentric strength curves of the elbow flexors were described for two groups of normal male subjects (Table II-3).[22,23] Based on the data extrapolated from these studies, the curves were modified as previously described (p. 17) and plotted (Figure 8). In both cases, ascending-descending curves were described although the angles of peak torque occurred at 55°[22] and 100°[23] of elbow flexion. This marked variation in angle of peak torque is difficult to explain. A lack of

Table II-3 Free Dynamic Elbow Flexor Curves

Author(s)	Body Position	Shoulder Position	Forearm Position	Subject Age	Subject Sex	Subject Occupation	Measuring Tool
Doss & Karpovich, 1965[22]	standing	adducted; neutral	-	19-23 yrs.	37 M	junior college men	special dynamometer
Singh & Karpovich, 1966[23]	sitting	adducted; shoulder yokes	supinated	20-25 yrs.	20 M	P Ed students	special dynamometer
Knapik et al., 1983[25]	sitting	adducted; neutral	midposition	26.1±3.8 24.9±4.1	16 M 15 F	mostly soldiers	modified N-K table

Figure 8

Free Dynamic Elbow Flexor Strength Curves



adequate stabilisation and isolation of the elbow flexors may have affected the results of the first group of subjects who were measured in standing while gripping a handle. However, marked acceleration-deceleration patterns have been described during so-called "free" arm curls. This could lead to the occurrence of erroneous peak and minimal values in the strength curve.[68] In a third study,[25] the pattern of effort closely matched the pattern of resistance provided by the equipment on which subjects were tested. Strength during concentric motion is thus extremely difficult to describe without the control of at least one main factor.

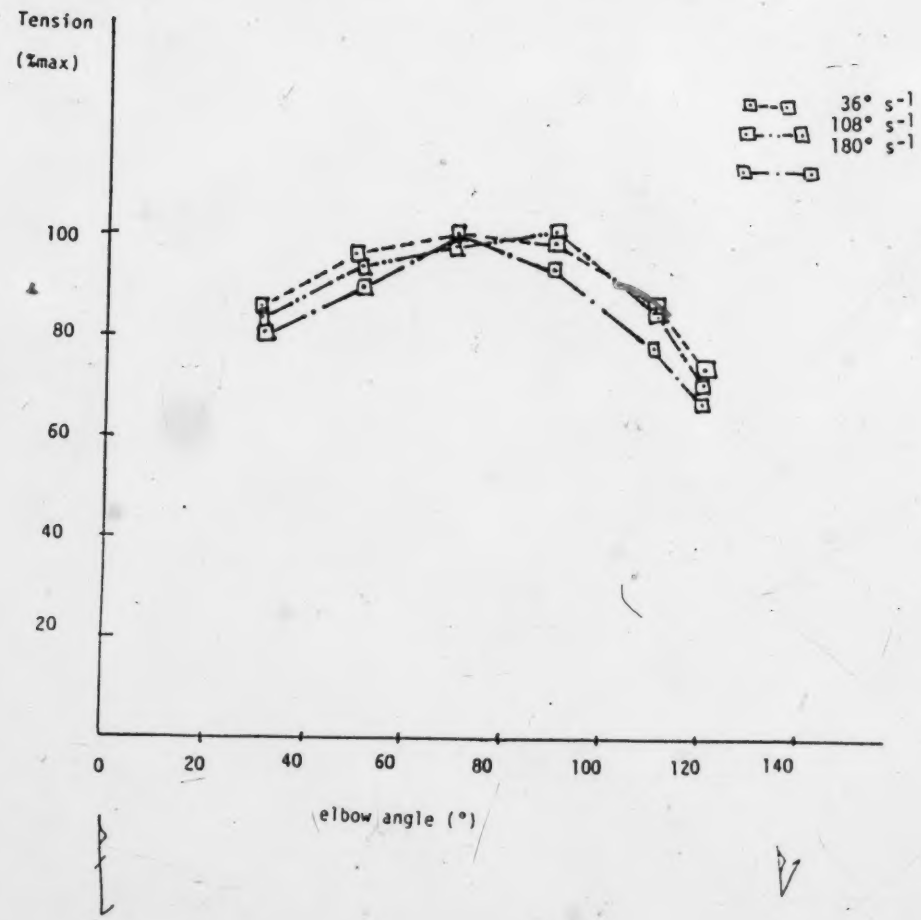
The introduction of isokinetic equipment on to the strength assessment and training market, has led to the possibility of more accurate descriptions of dynamic muscle strength in that the variation of muscle tension with length can be measured under controlled velocity conditions. Isokinetic strength curves have been described, though not extensively. One author derived isokinetic elbow flexor curves at speeds of 36, 108 and 180° per second.[25] Based on data extrapolated from the text, the modified curves have been plotted (Figure 9). In this case, peak torque varied between 70° and 90° although the overall shapes of the curves are similar to each other and to the previous curves, being also ascending-descending in shape.

Isokinetics

The concept of velocity-controlled or isokinetic movement was first introduced in 1967.[69] In uncontrolled velocity movements, energy is dissipated in accelerations which occur during

Figure 9

Isokinetic Elbow Flexor Strength Curves



movement.[69,70] Maximum tension is developed in one part of the range of motion only, while the rest of the movement is momentum dependent and measured torques submaximal. In free uncontrolled movements, it is difficult to predict where peak torque will occur[70] and effort does not necessarily follow the pattern of resistance.[69] An isokinetic device holds speed constant and absorbs the tension generated within a muscle group as attempts are made to accelerate a rotating limb segment.[69,71] The rotary effect of a muscle group around a joint axis can be measured as torque and the muscle group thought of as a torque-transmitting mechanism. The torque generated by the muscle group is proportional to the tension developed within the muscle at each joint configuration.[69,70]

The anatomical axis of rotation lies within the joint about which muscle torque is created. This torque is transmitted to the input arm of the isokinetic device by coupling the joint axis with the machine's axis of rotation.[71] The input torque varies with length-tension and leverage effects within the muscle group[69] and, for a given speed of shortening, the isokinetic device documents the maximum dynamic torque throughout the range of motion.[72] Torque is therefore speed-specific.

The coefficients of accuracy, linearity and speed consistency of the isokinetic device have been determined at 0.999, 0.995 and 0.985 respectively.[71] Thus, when properly calibrated, the machine is highly accurate and consistent. Certain sources of error are, however, associated with the use of isokinetic dynamometers. Speed in the isokinetic device is controlled by feedback control which prevents

joint angular velocity from exceeding the rotation of a motor driven axis.[73] When effort is applied against the input arm, a quick acceleration to the set speed occurs.[74] As the feedback control comes in to reduce speed and stop further acceleration of the limb segment, a moment is recorded. This overshoot torque does not represent muscle torque but is the torque required to decelerate the accelerating limb segment.[75]

The initial impulse is followed by a train of oscillations as the system regains its preset speed.[75] There are therefore three phases of movement - initial acceleration during which no torque is recorded; the initial part of the torque curve which consists of a train of oscillations; and the torque curve at constant velocity, after the oscillations have worn off. In slow movements, impact does not disturb the torque record for more than a few degrees of angular movement.[73] However, the manufacturers recommend that readings in the first one-tenth of a second be regarded as unreliable.[76] One way to reduce the effect of oscillations on the torque trace is to use the damp setting.[77] Care must be taken in the use of damp as this setting reduces the sensitivity of the recording instrument thus decreasing the amplitude of the entire curve and tending to shift the torque curve to the right.

Gravitational forces acting on the moving limb and input arm are not recorded in the torque curve. Contractions against gravity are therefore underestimated while those with gravity are overestimated.[74,78] Correction of the recorded torque is necessary when accurate values of muscle torque are required.[73] However, when

comparisons are made between external torques developed under the same conditions, the correction for gravity is not necessary.

Variable Resistance Machines

The theory of strength development that provides the rationale for fixed variable resistance machines is the principle of overload.[31] A muscle responds to overload by increasing its ability to generate tension. This is generally achieved by increasing the number of motor units that are recruited as well as increasing the synchronicity of firing of motor units. While this basic principle of strength training is not new, the magnitude of the load required to produce maximum strength gains has long been debated.[79] Several attempts have been made to determine the optimal strength training load. Various methods of training have been used with the effect that the load variable has been confounded by the other variables including number of sets, number of repetitions and method of testing. The optimum load for weight training appears to be a 6 RM load.[79] The effectiveness of training at 80% of a 1RM load has also been established. However, no attempt has been made to equate or compare 6 RM loads with 80%-1RM loads. After an extensive review of the literature, one author concluded that whereas a heavy load is essential in producing significant increases in strength, the heaviest loads do not produce the greatest gains.[79] The optimal load has not yet been determined.

Variable resistance machines provide resistance to selected motions that varies in such a way as to precisely match the

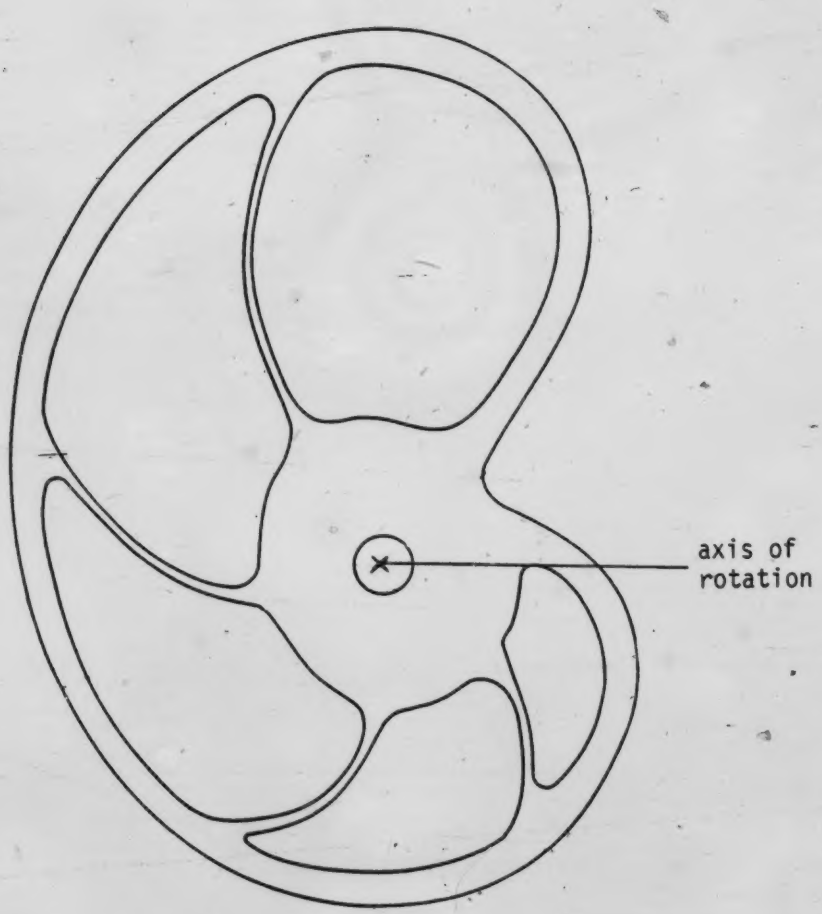
corresponding strength curve.[1,31] If appropriately derived, dynamic strength curves provide the basic data needed for the design of variable resistance machines.[31] Similarly, if appropriately designed, fixed variable resistance machines will overload a muscle group throughout its entire range of motion.[79] The strength benefit to be derived by fixed variable resistance loading is therefore thought to be superior to that derived from traditional forms of exercise and equipment. Constant resistance training or training against gravity tends to tax the muscles to their limit only at one critical angle, the 'sticking point'. This is generally the weakest point in the range and the load lifted is limited to that which can be lifted at the sticking point. The load that can be experienced in other parts of the range of motion may then be significantly less than the available maximum.[80]

The effect of resistance pattern on training has been studied,[81] though not extensively. A Noland-Kuchoff (NK) table capable of producing a variety of resistance patterns was used to reverse the normal pattern of loading in a muscle working against gravity. Training was carried out in the normal and reversed patterns. Changes in strength were documented at three angles, and muscle strength was found to vary in different ways in each angle. Tentative findings suggest a specific training effect at each angle, with a maximum effect at the most heavily loaded angle.[81]

In the NEFM the resistance pattern of the plate loaded resistance arm is modified by the use of a Nautilus-shaped cam (Figure 10). The variable resistance pattern of the machine has not, however, been described. In order to produce a pattern of strength gain that is

Figure 10

The Nautilus Cam



consistent with functional requirements, the machine's resistance pattern should match the strength curve of the elbow flexors. The description of both these patterns will make it possible to make appropriate comparisons.

Summary

Strength curves represent the maximum capability of a muscle group to develop tension at various joint angles, and under specific conditions. Both static and dynamic strength curves of the elbow flexors have been described. Static curves are mainly influenced by the length-tension relationship of muscle and biomechanical lever arm effects. Dynamic strength curves also take into account the force-velocity relationship of muscle, and thus are more applicable to functional situations. Dynamic curves can therefore provide the basic data required for the design of variable resistance machines. Variable resistance machines attempt to overload a muscle group at all points in its working range of motion so that maximum strength gains may be achieved. Resistance is provided that varies in such a way as to precisely match the muscle group's strength curve. However, variable resistance machines are usually isotonic and do not allow for control of the acceleration-deceleration components of free movements. These components serve to vary the resistance load of these machines in unpredictable ways and may therefore alter their proposed effect. In order to optimise the use of the available resistance pattern, isotonic movement should be performed at near constant velocity.

Isokinetics are velocity controlled movements. An isokinetic

device provides a means by which velocity of movement can be controlled and the interaction of muscle force with joint angle can be observed. The torque developed on an isokinetic device can be specifically related to a given joint position and is speed specific. Isokinetic strength curves are therefore useful as a basis for comparison of variable resistance machine patterns. However, such isokinetic curves should take into account factors such as body position and stabilisation which may significantly affect the shape of the derived curve. In the case of the NEFM, it is possible to compare the resistance pattern experienced at constant velocity movement with the isokinetic strength curve of the elbow flexors.

CHAPTER III

MATERIALS AND METHODS

Determination of EFCP

Subjects. Twenty-five female volunteers served as subjects in the study. Subjects were screened to ensure that they had no history of systemic pathology or significant upper limb injury. None of the subjects was involved in sports or training programs that required predominantly the use of the upper limbs. All subjects were required to give informed consent (Appendix A).

The subjects ranged in age from 19 - 29 years; in weight, from 40.0 - 73.6 kg; and, in height, from 152.2 - 178.1 cm. Subjects anthropometric data are summarised in Appendix B.

Subject Positioning. The test position used replicated that used on the NEFM (Plate 1). The test apparatus was set up to conform with measurements of the dimensions of the NEFM. Subjects sat upright with feet flat on the floor. Both upper limbs rested on a cushioned wedge with hands together and touching in the midline, forearms fully supinated and palms up. Both wrists were held in the semi-flexed position as the subjects grasped the effort application bar. The subjects' elbow joint axes, approximately located at the lateral epicondyles,[23,25,82] were aligned with the axis of rotation of the input shaft of a Cybex II+ isokinetic dynamometer* while the elbows were maintained in full extension. Seat height was adjusted, for

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* Cybex Division of Lumex, Inc.,
Ronkonkoma,
New York 11779, U.S.A.

Plate 1

comfort and ease of movement, by the use of additional seat raises. If necessary, additional foot support was provided so as to maintain a 90° angle at hips and knees.

Experimental Procedure. Basic anthropometric measures including height and weight were taken as described in Appendix C. Other measurements included forearm, hand, and forearm-hand lengths. The test-retest reliabilities of these measures were established (Appendix C).

The torque and goniometry channels of the isokinetic dynamometer were calibrated according to the manufacturer's recommendations.[76] The torque channel was calibrated for a full scale deflection of 90 ft.lbs. The subjects' elbows limbs were maintained in full extension while the effort application arm of the machine was aligned parallel with a line joining the elbow joint axis to the point where the hand grasped the grip bar. The input arm was not perfectly parallel with the forearm but the deviation was estimated to be not greater than 5°. This was not considered to be a significant deviation.

Stabilisation was limited to that which the subject would normally experience during use of the NEFM. General body stabilisation was achieved actively as subjects were required to maintain contact with the seat and the floor or foot support during testing. Stabilisation of the proximal and distal joints was achieved by subjects actively depressing their shoulders and maintaining their wrists in a semiflexed position. No external stabilisation was applied to the subjects. However, the anterior edge of the testing table was stablised manually to prevent backward tilting during the test movement.

Isokinetic testing was carried out at two velocities. The 'slow' speed was $60°s^{-1}$ while the 'fast' speed was $90°s^{-1}$. Both speeds are extremely slow when compared with speeds that the elbow flexors are capable of generating.[24] The designation of 'fast' and 'slow' were used to facilitate discussion and description to subjects. The fast speed approximates that recommended by the Nautilus equipment manufacturer who suggests that the movement be completed in 1 - 1 1/2 seconds. The slow speed was selected as preliminary work showed that this was slow enough to enhance force development yet fast enough to avoid marked effects of fatigue on maximum efforts sustained over such a large range of motion.

Subjects were randomly assigned the order of testing speed. After being set up, they were each allowed several submaximal trials to familiarise themselves with the equipment. During these trials, the alignment of the subject with the machine was also checked. When properly aligned, the subject was able to complete the required motion smoothly and without experiencing tension or compression in the elbow joint or at the hand.[76] When necessary, subjects were realigned prior to testing.

Three maximal trials of elbow flexion were conducted at each speed. The movement began in full elbow extension and ended in elbow flexion with the subject's hands contacting the chest, chin tipped slightly upwards to avoid contact at this point. Subjects were instructed to pull as hard and as fast as possible without jerking the movement. Verbal encouragement was standardised as a single command given forcibly at the initiation of each repetition, "Now, pull!"

During the actual test sequence, two submaximal trials were performed first, each followed by 30 seconds rest. After this, three maximal trials were each followed by 60 seconds rest. Both test speeds were completed in succession.

The maximal efforts were recorded on a dual channel heat sensitive chart recorder.* Torque was recorded on one channel and angle on the other. The angle recorded was that of the machine's input arm, which maintained its approximately parallel relationship to the subject's forearm throughout the range of motion.[23-25] The paper speed was maintained at 25 mms^{-1}. A damp setting of 3 was used. The torque scale was 90 ft.lbs. for a full scale deflection in all cases except three, where the 30 ft.lbs. scale was used. A sample trace of the Cybex data appears in Appendix D.

Data reduction was performed according to a standard procedure. The elapsed angle from initiation of motion was first determined from the height of the goniometer trace. Torque was read from the torque trace at 10° intervals and recorded in ft.lbs. (Appendix D). The range of motion achieved by each subject was determined as was the minimum and average range of motion (Appendix D). The starting position of the movement was taken to be the 0° position. The average range of motion achieved by the subjects was 150°. Data reduction was therefore performed in 10° increments over the range of 10° to 150° of motion. Torque was then averaged over each of the selected angles and for each

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* Cybex Division of Lumex Inc.,
Ronkonkoma,
New York 11779, U.S.A.

speed. The averaged torque data was then converted to percentage of maximum.

Analysis. Statistical analysis of the Cybex data involved the application of a three-way analysis of variance[83] to test for main effects and possible interaction of the factors speed, trial and angle. Factor A, speed, had two levels - $60°s^{-1}$ and $90°s^{-1}$; Factor B, trial, had three levels - trials 1, 2 and 3; Factor C, angle had 15 levels - angles 10° to 150° in 10° increments. The acceptance level of significance was set at .01.

Indirect Determination of NEFM Resistance

Mathematical Model. In order to determine the resistance pattern of the NEFM, the major mechanical features of the machine were mathematically modelled. The model was based on the assumption of a friction-free and acceleration-free system. The constant velocity condition was imposed since only movement at constant speed makes full use of the resistance pattern provided by the machine.[80] Newton's laws of statics[50] were applied to the model. Moments due to the various machine components were balanced and assumed equal to the effort moment which a subject would have to apply to the machine's effort application arm. Two systems of balanced moments were identified (Figure 11).

System 1 (Figure 12) consists of the weight arm (WA) and force (F) on the chain to the cam. Both rotate about a fixed common axis. Movement in this system is an upward rotation caused by the force of the chain. The resistance moment causes a downward rotation due to the weight of the weight arm (W_{WA}) and to any external weight (W) applied

Figure 11

Mathematical model of NEFM

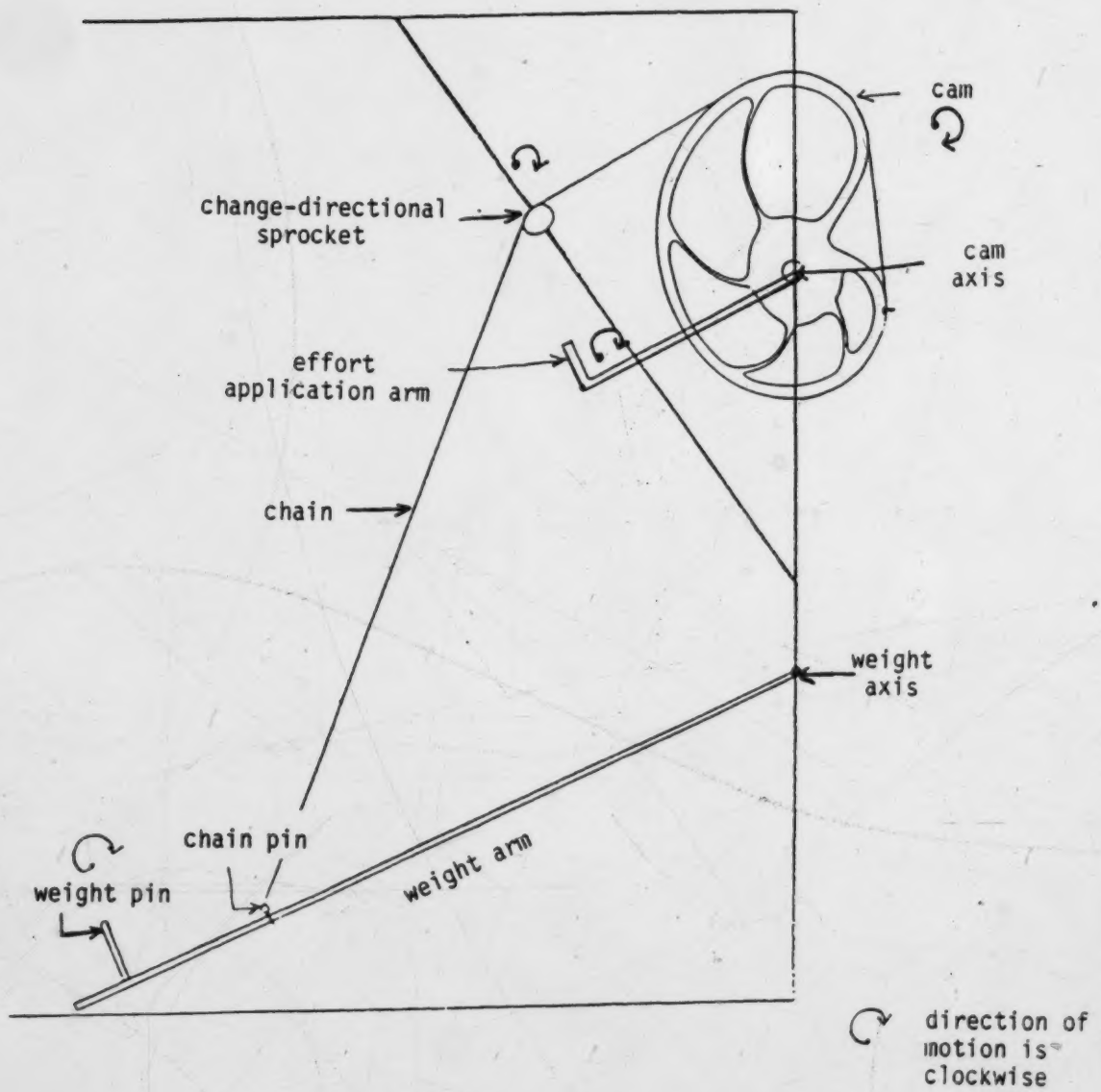
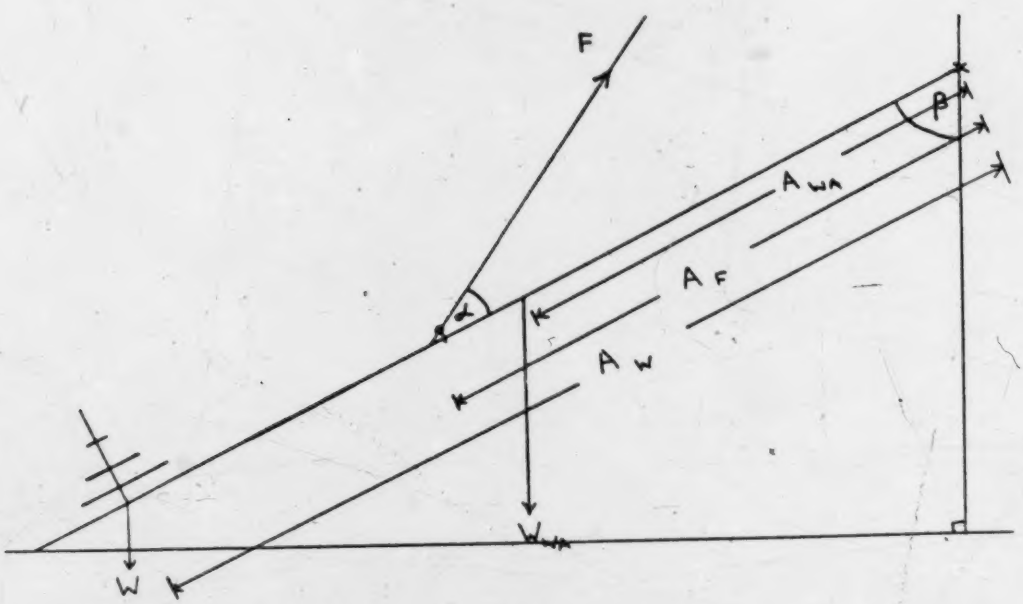


Figure 12

NEFM System 1



Chain torque = Resistance torque

$F \sin \alpha^{\circ}(A_F) = W_{WA} \sin \beta^{\circ}(A_{WA}) + W \sin \beta^{\circ}(A_W)$

where,

F = force along the chain (kg.)

α = angle between weight arm and line of pull of chain ($^{\circ}$)

A_F = application arm for F (distance from axis of rotation of weight arm to chain pin (cm.), measured along the weight arm).

W_{WA} = weight of weight arm (kg.)

β = angle between weight application arm and the vertical ($^{\circ}$)

A_{WA} = application arm for weight arm (distance from axis of rotation of the weight application arm to centre of gravity of weight application arm (cm.), measured along the weight application arm).

W = weight on weight arm (kg.)

A_W = application arm for weight (distance from axis of rotation of weight arm to weight pin (cm.), measured along the weight arm).

to the WA at the weight pin. These resistance forces act through application arms A_{WA} and A_W respectively. The moment generated by W_{WA} is:

$$W_{WA} \sin \beta \cdot A_{WA}$$

and, the moment generated by W is:

$$W \sin \beta \cdot A_W$$

where β = angle between WA and the vertical at the axis of rotation.

The effort moment in System 1 is provided by the force developed in the chain. During constant velocity movement, this force must generate a balancing moment such that the sum of the moments (ΣM) = 0.[49] The chain force (F) acts through application arm A_F and creates a moment:

$$F \sin \alpha \cdot A_F$$

around the same axis as the resistance moment such that:

$$F \sin \alpha \cdot A_F = W_{WA} \sin \beta \cdot A_{WA} + W \sin \beta \cdot A_W \qquad (i)$$

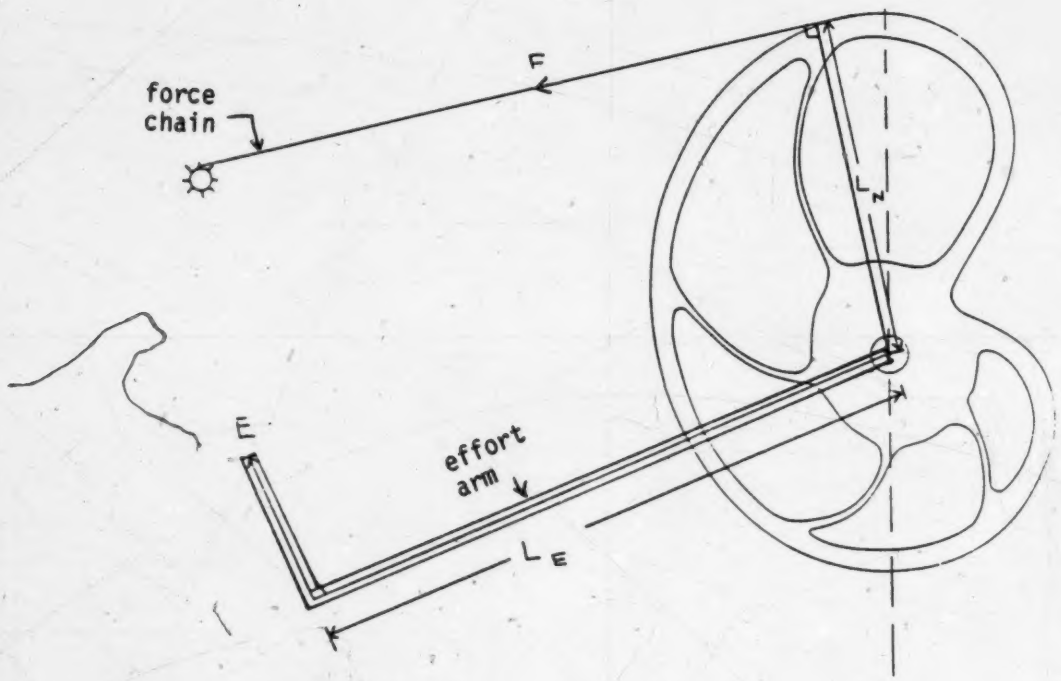
System 2 (Figure 13) consists of the chain force (F) converted to torque via the Nautilus-shaped cam, and the effort arm (EA) which converts force applied by the subject (E) into torque by providing an appropriate lever arm (L_E). The effort moment is, therefore:

$$E \cdot L_E$$

The two components of System 2 share a fixed axis of rotation. The movement that occurs during lifting is an upward rotation of the effort application arm. The resistance moment is supplied by the chain force acting through a lever arm, the length of which is determined by the position of the cam (Figure 14). The perpendicular distance from the axis of rotation to the line of pull of the chain changes as the cam

Figure 13

NEFM System 2



$FL_N = E.L_E$

where,

E = effort force (kg.)

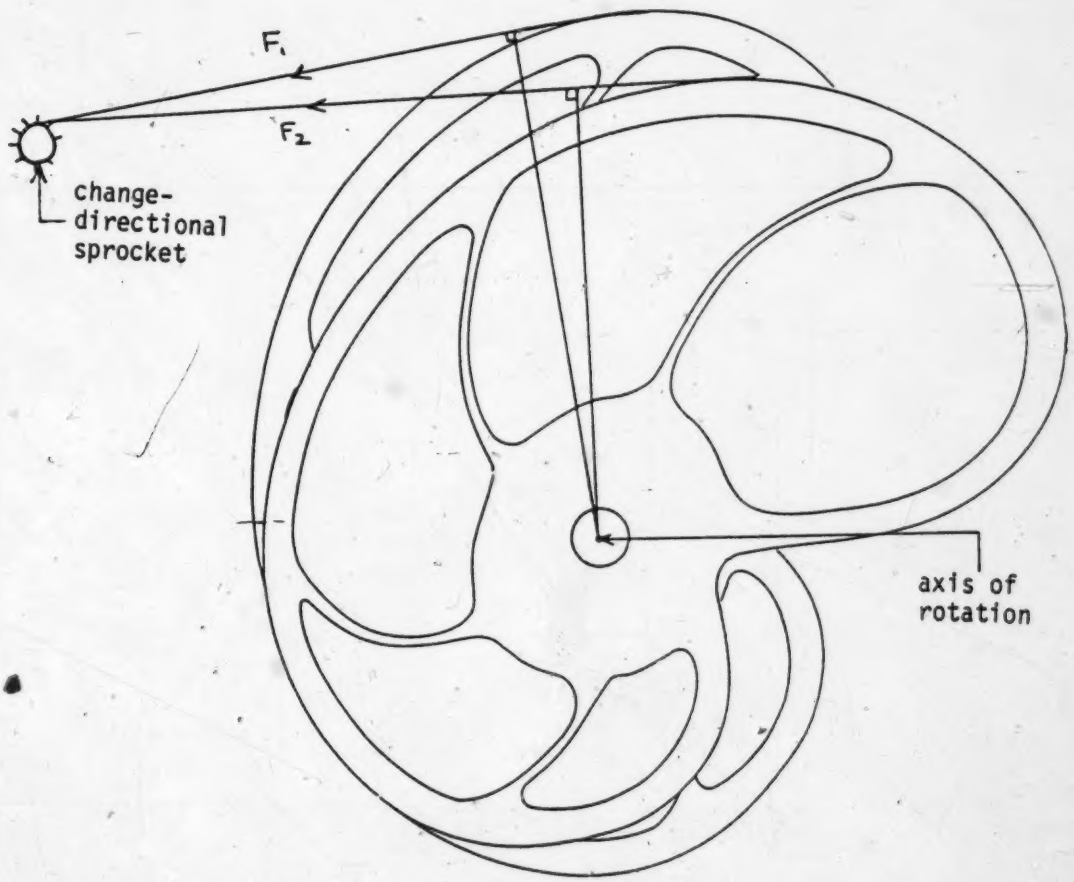
F = force on the chain (kg.)

L_N = perpendicular distance from chain to cam axis (cm.)

L_E = perpendicular distance from point of application of E to axis of rotation of cam (cm.)

Figure 14

Changing Lever Arm of Nautilus Cam



rotates. This distance represents the effective lever arm of the chain force (L_N). The moment due to the resistance is, therefore:

$$F \cdot L_N$$

In System 2, effort and resistance moments are balanced such that:

$$F \cdot L_N = E \cdot L_E \qquad \text{(ii)}$$

Analysis of the resistance components of the machine was based on the determination of $F \cdot L_N$. F was calculated on the basis of equation (i), rearranged such that:

$$F = \frac{W_{WA} \sin \beta \cdot A_{WA} + W \sin \beta \cdot A_W}{\sin \alpha \cdot A_F} \qquad \text{(iii)}$$

The determination of F was based on measurements of each of the major components of the NEFM system. The individual effect of each component was examined as was the interaction of the various components in producing the final resistance pattern.

Experimental Procedure

In order to determine F, the relevant values were determined as described. Angular values were measured by manual or pendular goniometry. Manual goniometry was carried out with a 360° protractor type goniometer* while pendular goniometry was performed using a small, commercially available instrument.** Although goniometry is generally

---

* Be-OK! International Standard Goniometer
Fred Sammons Inc.,
A. Bissell Health Care Co.,
Box 32,
Brookfield, Ill. 60513, U.S.A.

** O.B. Vinklmatare "Myrin",
O.B. Rehab-Produkter,
10051 Stockholm, Sweden.

linked with many potential sources of error, the standardisation of goniometric technique, accurate localisation of the axis of rotation, and proper alignment of goniometer arms with the long axes of the fixed and/or rotating arms, greatly improve the accuracy of such measures.[83,85-88] With pendular goniometry there is the main advantage of not having to locate the axis of rotation since these instruments are gravity-dependent.[89,90] High reliabilities have been reported with the use of pendular goniometers as long as movement is confined to one plane.[90] However, pendular goniometry requires that the moving arm be able to support the goniometer. This was not possible in the determination of α, therefore a manual goniometer was used. Coefficients of reliability of the angular measures are given in Appendix E. The angular value of α, the angle between the weight arm and line of pull of the chain was measured, in degrees, by manual goniometry. The angular value of β, the angle between the weight application arm and the vertical was measured, in degrees by pendular goniometry. Values of α and β were determined for each of the preselected angles of the EAA.

Standard precision weights (W) were used to load the weight arm with 4.54 to 18.14 kg. in increments of 2.27 kg. The weight of the weight arm was measured directly using a precision balance,* which provided a digital read out in grams, to the nearest 0.1 g.

Linear distances were measured using a standard steel tape

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* Mettler PE 16 Electronic Weighing Scale,
Mettler Instrument Corporation,
Box 71
Hightstown, NJ 08520, U.S.A.

measure placed along the long axis of the object to be measured. The distance from the axis of rotation of the weight arm to the centre of the weight pin (A_W) was measured in cm. The centre of gravity of the weight arm was located using the balance method;[49] the distance from the axis of rotation to the centre of gravity of the WA (A_{WA}) was then measured. The distance from the axis of rotation of the weight arm to the centre of the chain pin (A_F) and the values of L_N were also directly measured. Each measurement of L_N was repeated twice and the mean values and test-retest of reliability (r) determined (Appendix E). Each of the other measurements were repeated four times and the mean values and reproducibility determined (Appendix E).

Several measurements were related to selected angles of the EAA, i.e. α , β, L_N. During the taking of these measurements, an assistant rotated the EAA to the required positions and held the arm steady at 13 angular increments of 10° each. Only 130° of motion were available while performing on the NEFM.

Analysis. On the basis of the measurements taken, values of $F \cdot L_N$ were calculated for each level of load and at each angular position of the EAA. The resulting torque values were converted to %max torque, where maximum torque was designated as the peak value occurring for a given weight applied to the WA. %max torque was then plotted against angle to provide the predicted NEFM resistance curve. The equation of the derived line was determined using linear regression.[83]

The predicted curve based on the mathematically determined values, was compared with the observed dynamic performance curve, and also with the EFCP using descriptive statistics.[11]

Direct Determination of NEFM Resistance

Equipment. The NEFM resistance pattern was determined directly by the measurement of the pattern of torque developed on the EAA, according to the equation:

$$F \cdot L_N = E \cdot L_E$$

Actual values of $E \cdot L_E$ were not established but the bending effect produced at the base of the EAA was assessed in arbitrary strain units. The essential measuring tool was a system of strain gauges* located at the base of the EAA (Plate 2), and arranged in a full Wheatstone bridge circuit (Figure 15). The gauges are small electrical components that respond to bending by a change in length. This change in length, or strain, is reflected in a change in electrical resistance. With the bridge balanced at the resting position, bending movements applied to the EAA tend to imbalance the bridge proportionately. This effect is maximised at the base of the lever arm.[91] As bending alters in response to effective resistance throughout the range of motion, changes in the amount of strain were measured as electrical signals and recorded simultaneously with movement.

The output signal from the strain gauges was amplified** and

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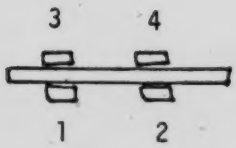
* Electric strain gauge CEA 062 UW 350
(Gauge factor 2.085)
Micromeasurement,
Supplied by Intertechnology,
P.O. Box 219
Don Mills, Ontario, Canada

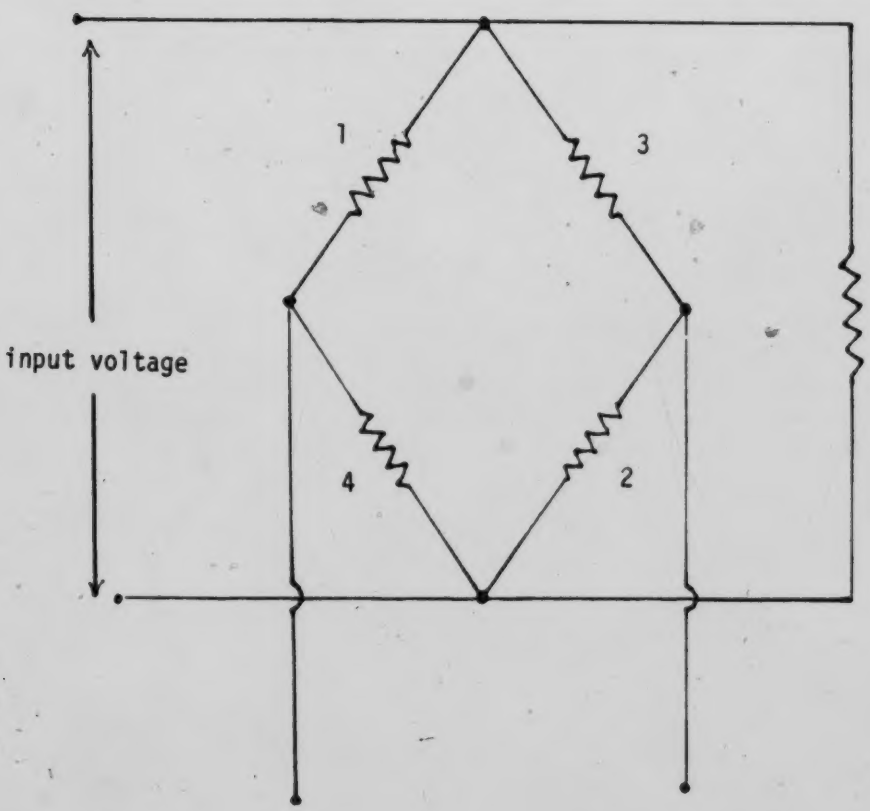
** Vishay BAM-1 Wheatstone Bridge Amplifier
Vishay Instruments Inc.,
63 Lincoln Highway,
Malvern, Pennsylvania 19355, U.S.A.

Plate 2

Figure 15

Wheatstone Bridge Circuit





recorded on 1-channel of a 4-channel thermal recorder.* The system was calibrated by applying precision weights to the EAA at a fixed distance (i.e. at the junction of the grip bar and main supporting frame) from the axis of rotation. Linearity was checked at three angles representing the midpoints of outer, middle and inner ranges, and the system was found to be highly linear ($r = 0.999$).

Experimental Procedure. A trained assistant lifted the effort application arm through its range of motion at approximately constant velocity. Velocity control was facilitated by the use of a metronome, and the preset velocity was $22.0°s^{-1}$. The assistant was seated at the NEFM in the standard position. During testing, the assistant's forearm was maintained on the elbow rest of the machine with the elbow joint in full extension and the elbow joint axis aligned with the axis of rotation of the EAA. The NEFM curve was evaluated with weights of 4.54 to 18.14 kg. in 2.27 kg. increments applied to the WA. Two trials were completed in succession at each weight value. The NEFM was completely unloaded and the zeroing of the bridge checked after each set of measurements.

On one of the remaining channels of the recorder, an electrogoniometer simultaneously recorded the angle of the EAA. The instrument consisted of a round rheostat and two shafts[92] that could be easily aligned and applied to the NEFM. The parallel alignment between the subjects' forearm and the effort lever arm was observed to

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* Hewlett-Packard 4-channel Thermal Tip Recorder, HP 7754A,
Hewlett-Packard/Medical Electronics Division,
175 Wyman Street
Waltham, Massachusetts 02154, U.S.A.

change minimally throughout most of the range of motion. The electrogoniometer was taped securely in position with the rotational axis of the potentiometer aligned with the rotational axis of the EAA. One arm of the electrogoniometer was aligned along the vertical supporting bar of the NEFM and the other appropriately bent at right angles so that it could be applied securely to the EAA (Plate 3). The electrogoniometer was calibrated against the pendular goniometer and, in order to reduce errors due to any lack of linearity, the actual levels on the chart strip that corresponded to the selected angles were directly recorded.

Analysis. Data reduction was performed according to a standard procedure. Arbitrary units of strain were read from the data strip for all preselected values of angle (Appendix F). Strain was then averaged over each angle and for each load. The average strain was then converted to %max strain, where maximum strain was designated as the peak value occurring at each load (Appendix F). %Max strain was then plotted against angle for each load value to provide a series of measured NEFM resistance curves. The equation of each line was determined using linear regression.[83] The measured NEFM curves were compared with the predicted curves and the EFCP using descriptive statistics.[11] One-way analysis of variance with repeated measures[83] was used to test for the effect of load on %max strain. The acceptable level of significance was set at .01. Post-hoc pairwise comparisons of means were performed using the Newman-Keuls' procedure.[83]

The time taken to move through every 10° of motion was measured

Plate 3

for each of two trials at each load (Appendix F). The time taken to complete the required movement was determined for each load. From this data, the average time taken and distance covered were used to determine the mean velocity of movement in degrees per second. The changes in velocity of movement for each part of the range of motion and at each load was also determined.

CHAPTER IV

RESULTS

The investigation of resistance and capability patterns during elbow flexion provides both descriptive and quantitative information. The present study was carried out under the assumption of constant velocity movement. The Cybex II+ isokinetic dynamometer was considered to provide valid and reliable data on the torque produced by the elbow flexors during movement. The mathematical model used to predict resistance in the NEFM was based on an idealised, friction-free system. The strain guage system used to measure the bending effects on the EAA also provided highly valid and reliable data.

The results of the study will be directly related to each of the stated objectives. Any additional points of interest will be noted where relevant.

Elbow Flexor Capability Pattern

The EFCP was based on the mean torque developed by 25 subjects at selected angles of the isokinetic dynamometer effort lever arm. The total mean range of motion achieved was 172.76°±9.97° while the average individual range of motion varied from 154° to 196°. The first 10° of movement was considered most unreliable due to torque overshoot and deceleration effects. Data in this range were therefore discarded. The EFCP was plotted over a range of 10° to 150° of movement.

The EFCP was determined at two speeds, $60°s^{-1}$ and $90°s^{-1}$. Both curves were ascending-descending. The curves rose at an almost constant rate to 40° and then at a slower rate, achieving a range of

peak torque between 110° and 130° and a distinct peak value at 120°. After this, torque declined slowly to 130° and then rapidly to 150°. Minimum values of torque occurred at 10° and 150° with the value at 150° being approximately three times that at 10° (Figure 16).

The $60°s^{-1}$ curve was separate and distinct from the $90°s^{-1}$ curve and lay above the latter at all points. The distance between the curves was less pronounced between 60° and 90° when the $60°s^{-1}$ curve dipped towards the $90°s^{-1}$ curve. When converted to %max, the curves were almost identical (Figure 17). The analysis of variance showed a highly significant main effect of angle at which torque was measured ($F_{(14,672)}$ = 122.10; p .000); there was no significant main effect of speed. The ABC interaction approached significance at the .01 level, however no significant interaction effects were found ((Appendix G).

The data from which the two curves were derived was combined and reduced to a single EFCP.

Predicted NEFM Resistance Pattern

The predicted NEFM resistance patterns were derived for selected loads applied to the WA. Moments in the NEFM were balanced under conditions of constant velocity and revealed a series of parallel curves of identical slope. When converted to %max, the relationship between torque and angle was constant for all values of W, i.e., weight applied to the WA. The %max value was found to be primarily dependent on the values of sin , sin β, and L_N (Table IV-1). The predicted NEFM pattern is therefore a single curve (Figure 18) independent of the weight applied to the WA. The %max values ranged from 65.48% to 100%

Figure 16

Elbow Flexor Capability Patterns in Ft. Lbs.

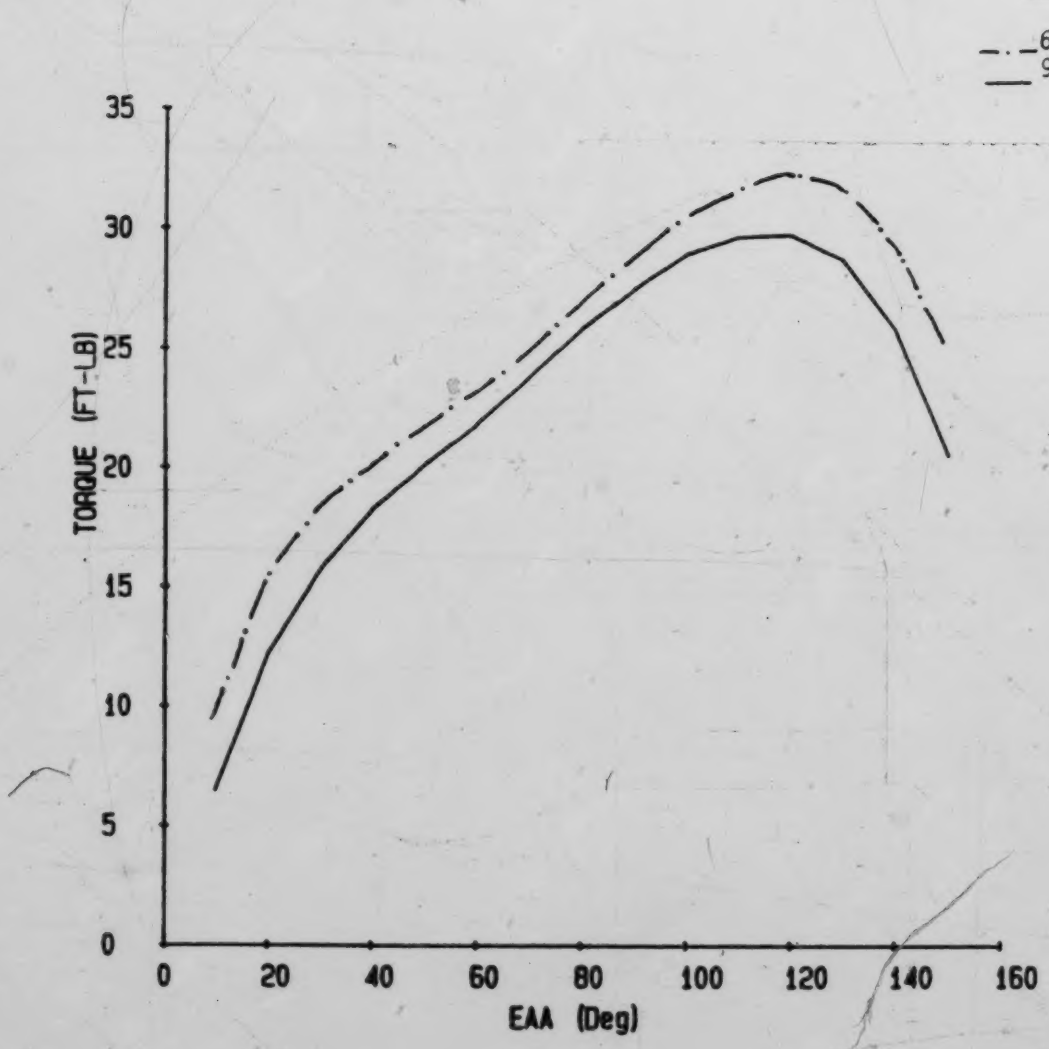


Figure 17

Elbow Flexor Capability Patterns in %max

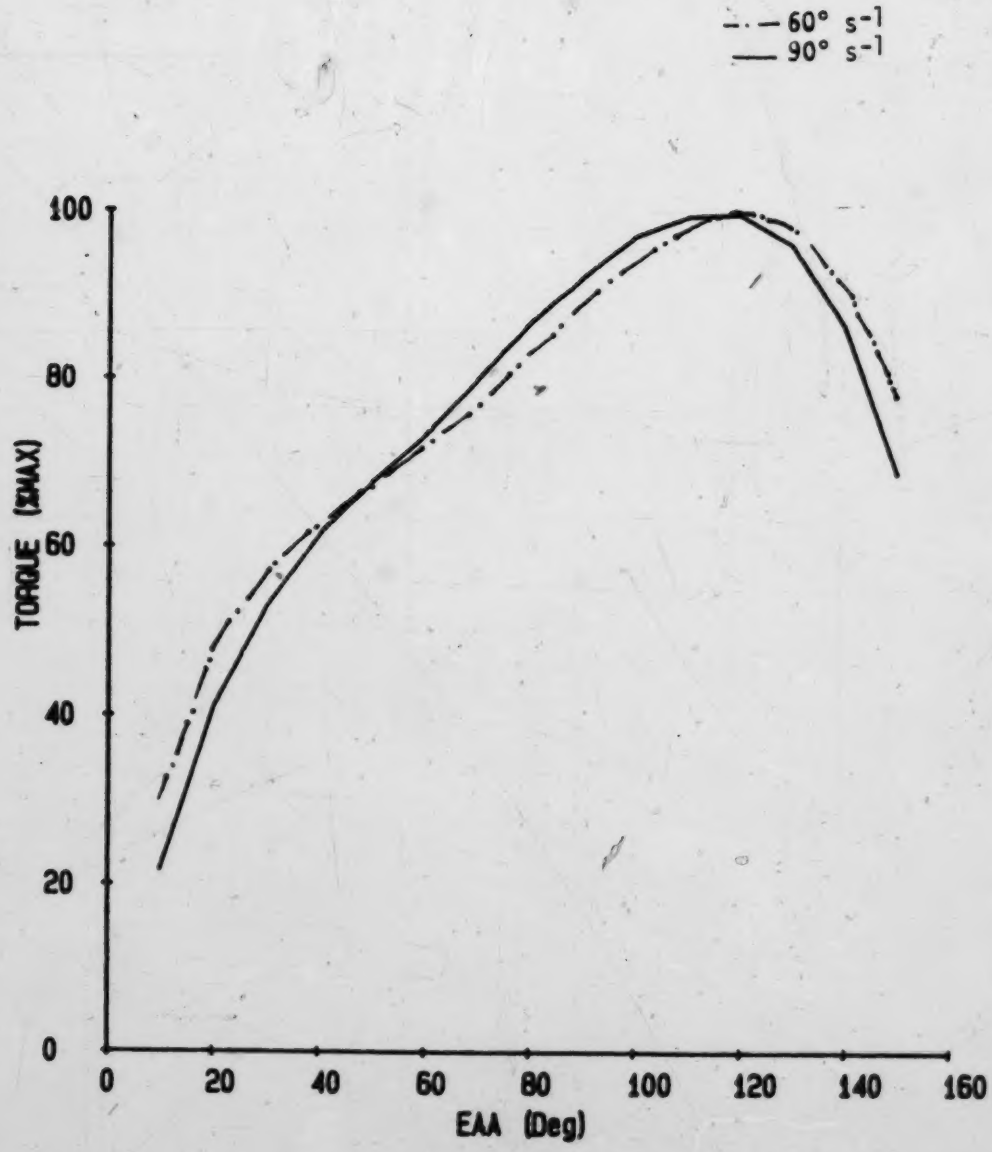


Figure 18

Predicted NEFM Resistance Curve

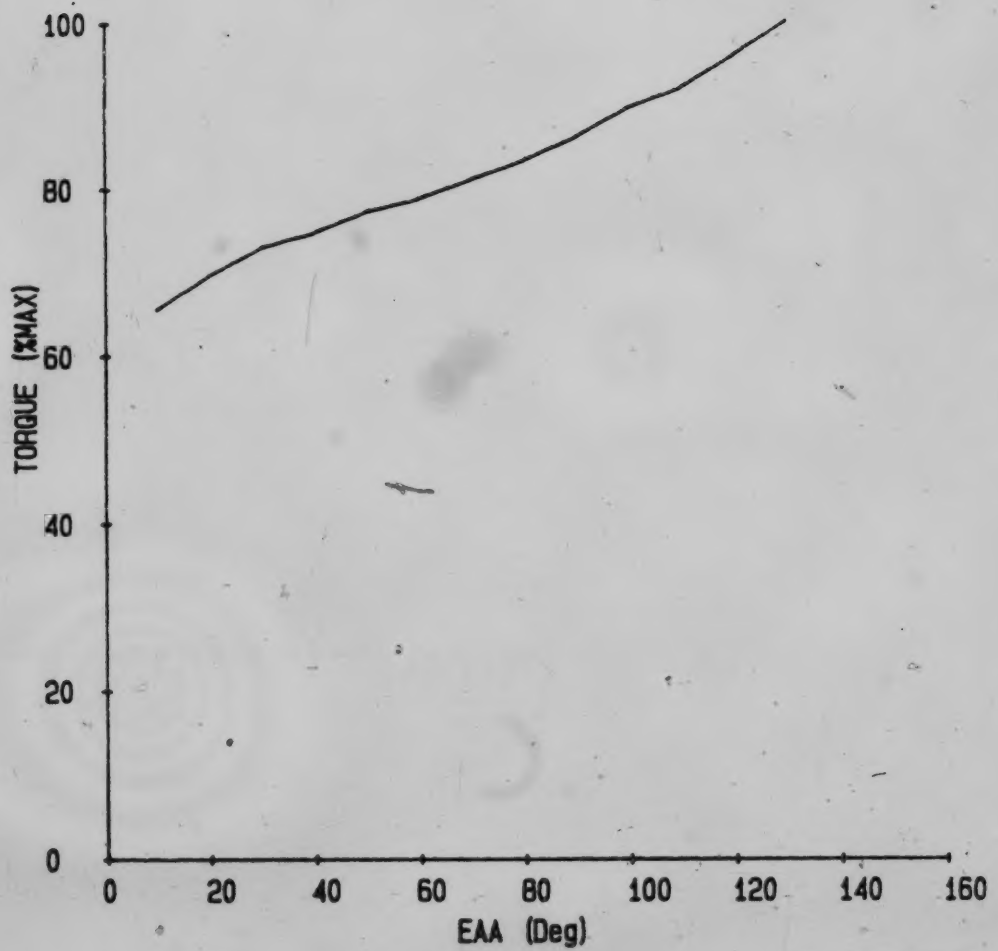


Table IV-1 Predicted NEFM %max Values

EAA°	β°	α°	sin β	sin α	L_N	$\frac{\sin \beta \cdot L_N}{\sin \alpha}$	% max
10	47.0	49.0	0.731	0.755	17.15	16.60	65.48
20	52.0	51.0	0.788	0.777	17.40	17.65	69.62
30	57.0	53.0	0.839	0.799	17.60	18.48	72.90
40	60.0	54.5	0.866	0.814	17.90	19.04	75.11
50	64.0	56.0	0.899	0.829	18.05	19.57	77.20
60	68.0	58.0	0.927	0.848	18.25	19.95	78.70
70	72.0	60.0	0.951	0.866	18.70	20.53	80.99
80	76.0	62.0	0.970	0.883	19.20	21.09	83.19
90	80.0	64.0	0.985	0.899	19.90	21.80	86.00
100	84.0	66.0	0.994	0.913	20.85	22.70	89.55
110	88.0	68.0	0.999	0.927	21.60	23.28	91.83
120	93.0	69.5	0.999	0.937	22.70	24.20	95.46
130	96.0	71.0	0.994	0.945	24.10	25.35	100.00

at 10° and 130° respectively. This range was selected as corresponding to the actual range of motion available to a subject seated at the NEFM. The curve was highly linear ($r = 0.994$) and could be described by the equation:

$$y = 63.6 + 0.262x$$

Measured NEFM Resistance Patterns

The measured NEFM curves were determined on the basis of strain produced at the base of the EAA as different loads were moved through the available range of motion at near constant velocity. Strain was measured in arbitrary units and converted to %max values. When plotted against angle, the data yielded a series of highly linear curves ($r = 0.994 - 0.999$) (Figure 19). There was a noticeable trend for the initial strain to increase with increasing weight so that although the curves were linear, their slopes varied progressively from 0.309 to 0.176 (Table IV-2). Equations which best described the curves were derived on the basis of linear regression (Table IV-2). Analysis of variance revealed a significant effect of weight applied to the WA ($F_{(42, 78)} = 9.35$; p .000) (Appendix G). Post-hoc pairwise comparisons of means using the Newman-Keuls' procedure[83] showed the effect of the 4.54 kg. load to be significantly different from all other loads except the 9.07 kg. load. However, there were no statistically significant differences between curves derived above the 4.54 kg load value.

The near constant velocity condition was assessed and mean velocity found to have been maintained at 22.21 $\pm$ 0.75°s^{-1} (Table IV-3). The pattern of performance was fairly consistent though even

Figure 19

Measured NEFM Resistance Curves

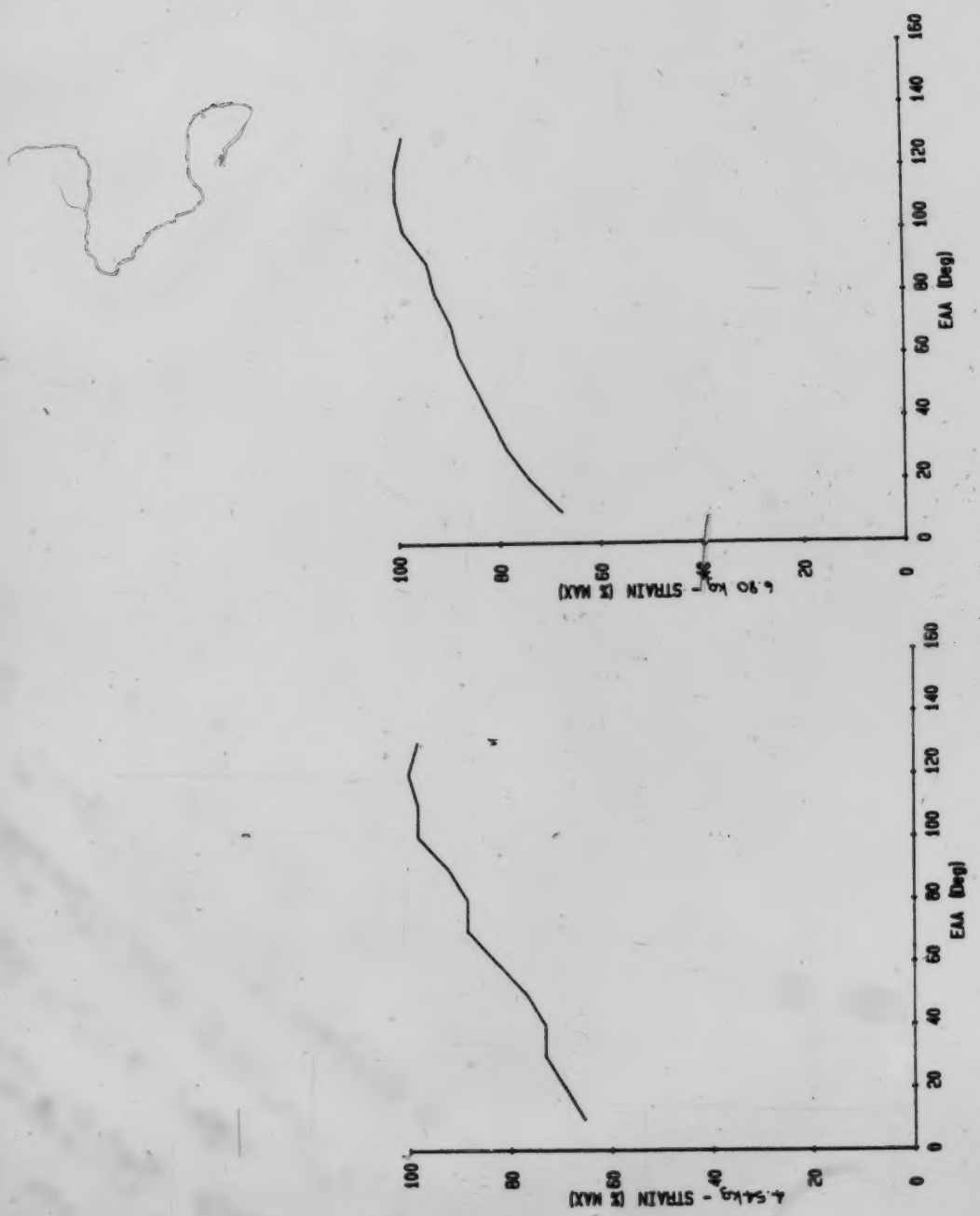
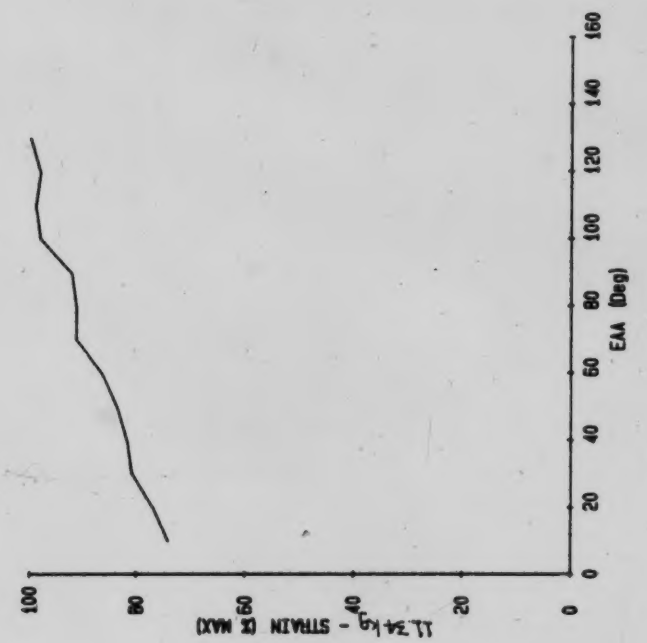


Figure 19 (continued)



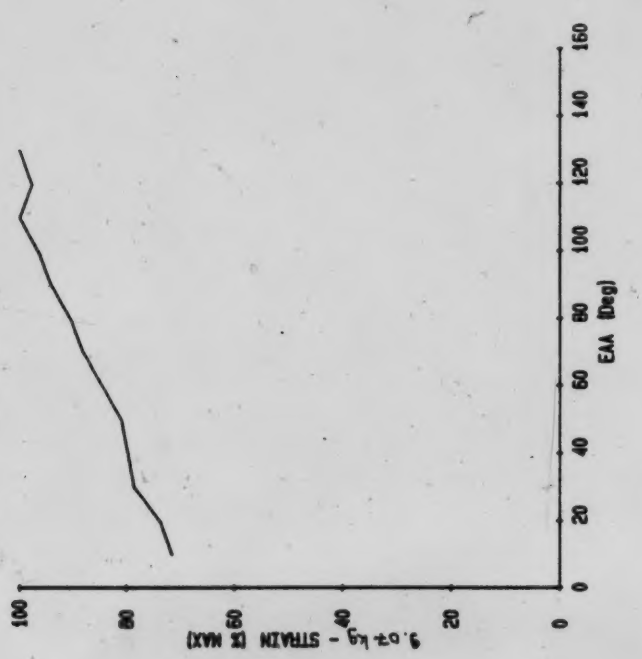


Figure 19 (continued)

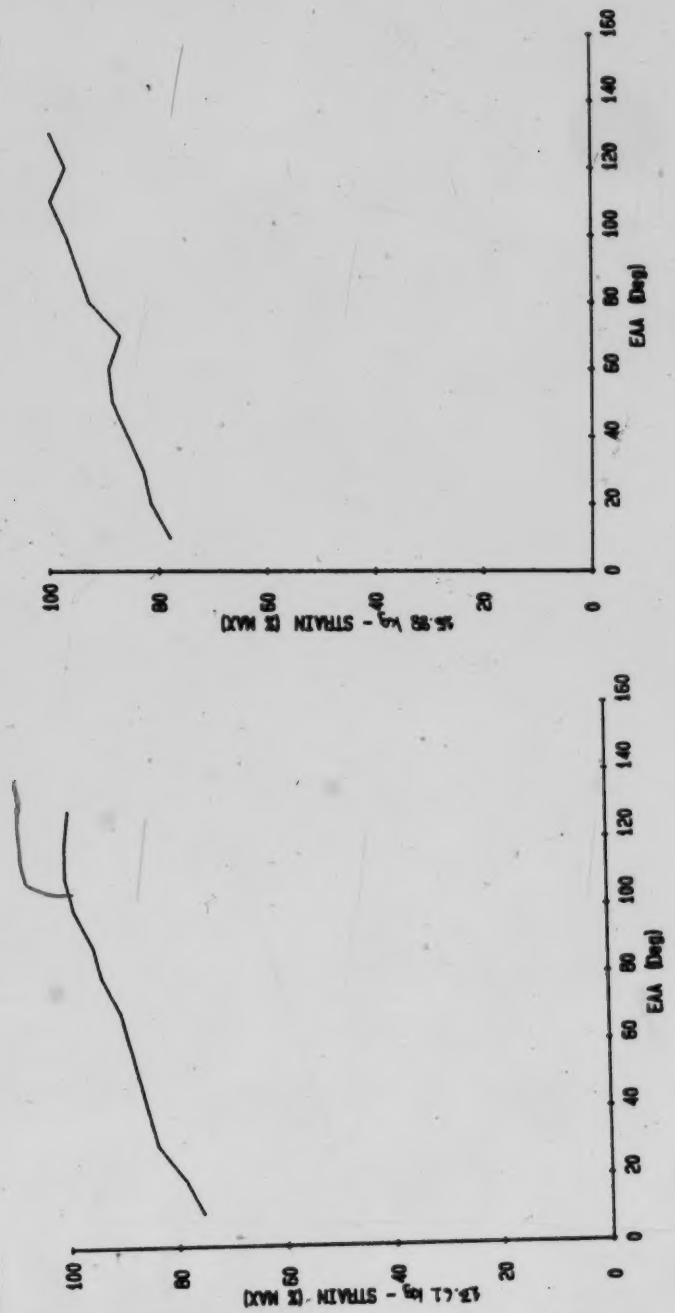


Figure 19 (continued)

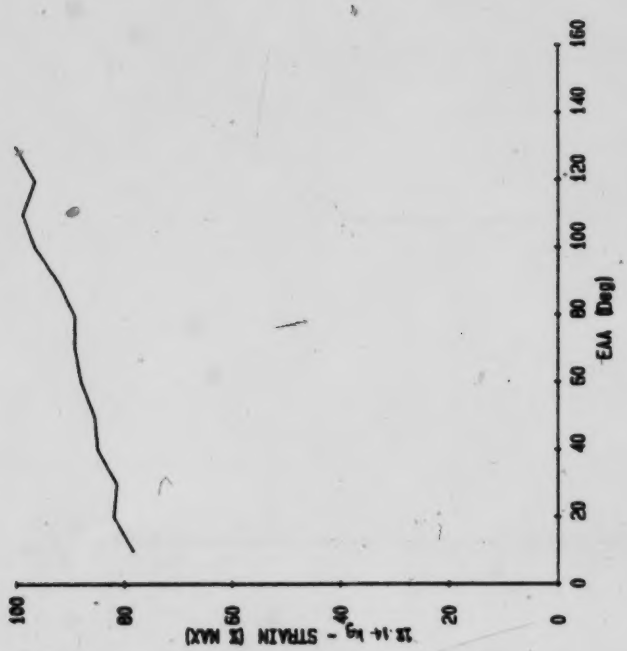


Table IV-2: Best Fit Curves of Measured NEFM Values

Load (kg)	Equation	R^2
4.54	y = 63.3 + 0.309 x	96.1
6.80	y = 69.9 + 0.261 x	94.2
9.07	y = 69.7 + 0.252 x	97.5
11.34	y = 73.1 + 0.223 x	97.0
13.61	y = 75.9 + 0.206 x	96.0
15.88	y = 77.7 + 0.182 x	94.7
18.14	y = 77.0 + 0.176 x	96.5

Table IV-3: Mean Velocity of NEFM Movement in Relation to Load

Load (kg)	Time (sec.)	Mean Velocity ($°s^{-1}$)
4.54	5.90	22.03
6.80	6.00	21.67
9.07	5.95	21.85
11.34	5.75	22.61
13.61	5.70	22.81
15.88	5.57	23.34
18.14	6.15	21.14
		$V = 22.21 \pm 0.75°s^{-1}$

with training there was a tendency to increase velocity above the desired level at the start of movement and then to move more slowly through the later range of motion (Table IV-4) (Figure 20).

Individual Component Contributions

The values of W_{WA}, A_{WA}, A_W and A_F remained constant throughout the range of motion and for all values of W. The weights applied to the WA were increased uniformly. The values of L_N and $\sin \alpha$ were found to increase throughout the range of motion. The value of $\sin \beta$ was maximal at the EAA angle of 110° and then decreased somewhat at 130° (Table IV-1). When converted to %max values, these trends were the same. However, the value of $\sin \alpha$, the angle between the chair and the WA, increased more rapidly than either $\sin \beta$ or L_N (Figure 21).

Table IV-4 Mean Velocity of NEFM Movement in Relation to Range

Range (°)	Time (sec.)	Mean Velocity ($°s^{-1}$)
10 - 20	0.55	18.18
20 - 30	0.45	22.22
30 - 40	0.37	27.03
40 - 50	0.34	29.41
50 - 60	0.36	27.78
60 - 70	0.29	34.48
70 - 80	0.37	27.03
80 - 90	0.53	18.87
90 - 100	0.61	16.39
100 - 110	0.69	14.49
110 - 120	0.63	15.87
120 - 130	0.66	15.15

Figure 20

Mean Velocity of NEFM Movement in Relation to Range

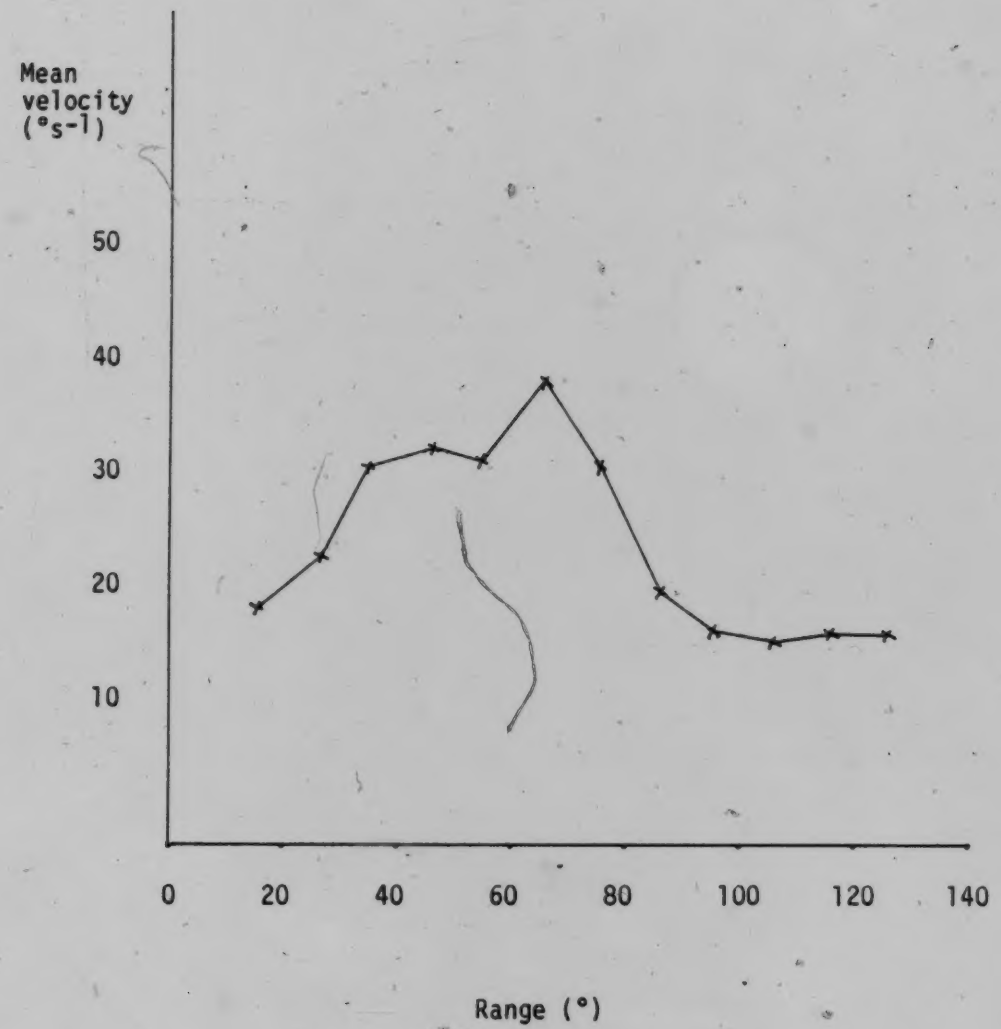
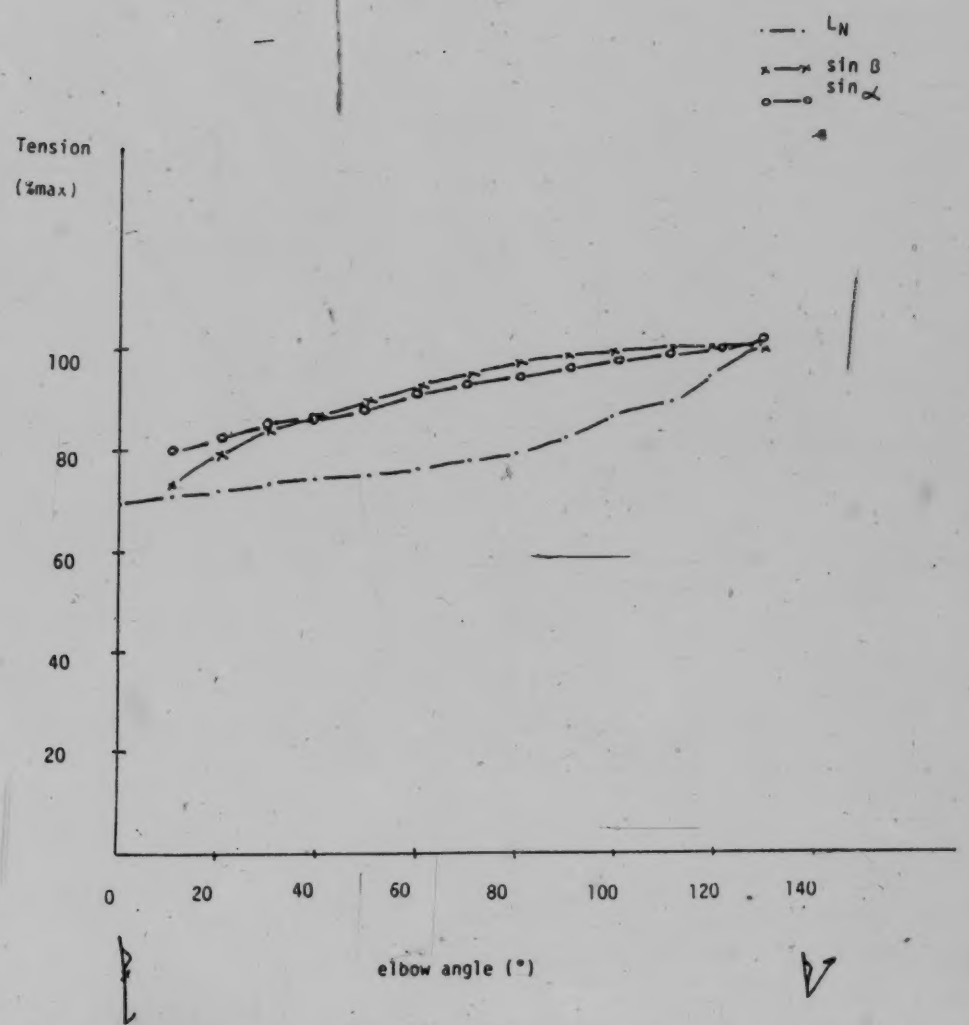


Figure 21

Resistance Component Combinations to Predicted NEFM Curve



CHAPTER V

DISCUSSION

Elbow Flexor Capability Pattern

The complex interaction of length-tension, angle of pull and force-velocity effects is clearly shown in the shape of the EFCP. This ascending-descending shape is consistent with that described in the literature[18-25] although there were some important differences.

The total range of movement achieved was greater than that predicted for the range of elbow flexion of normal females.[45] The main factor which contributed to this excessive range was that all subjects began the motion of elbow flexion in the fully extended or hyperextended position, thereby gaining approximately 15-20° of motion.[45] Adduction of the hands in the midline with external rotation of the shoulders and full forearm supination allowed approximation of the hands to the chest rather than to the shoulders thus avoiding the normal limiting factor of elbow flexion - the soft tissue contact between the forearm muscle bulk and the upper arm. At the end of the range of motion, slight internal rotation of the shoulders[40] and wrist flexion may have further increased the apparent range of motion. These accessory movements were not analysed directly but were considered to play a minor role. However, the last part of the EFCP was excluded from the comparative analysis with the NEFM resistance pattern.

The length-tension and angle of pull effects appeared to be the most significant factors in determining the shape of the curve. With the elbow flexors being in the lengthened position at the start of

movement, torque capability would be expected to be initially low with another minimum in the shortened position. The torque in the lengthened position was, in fact, less than that in the shortened position. This difference may be accounted for partly by the sliding filament theory of muscular contraction.[36] In the resting position, the number of crossbridge sites available for attachment are maximal.[15,36] In the lengthened and stretched position, several crossbridge sites lose their optimal relationship to each other, thereby reducing the number of available linkages.[15,36] Tension development capability is therefore reduced.

The reduced tension in the lengthened position was also largely due to the modification of torque development capability by mechanical features of the active muscle attachments. The angle of pull is significantly diminished, not only by extension, but also by hyperextension of the elbow joint. This is most likely true for all the major flexors as their insertions become flattened against the bones of attachment. The angle of pull is reduced and the mechanical advantage of a longer lever arm is lost.

The mechanical advantage of a wide angle of pull is said to be greatest in the 90° elbow flexion position.[49] This is usually consistent with the angle of peak torque.[18,20,21,24,25] In this study, peak torque occurred very distinctly at 120° with the highest range of torque values occurring between 110° and 130°. If the extra 15-20° of elbow hyperextension are taken into account, this could partly explain the late occurrence of the peak value of torque. It has been shown that with increased stretch, the length-tension curve is

achieved later in the range of motion due to the effect of stretch on the formation of crossbridge linkages.[63]

The effect of velocity on force development was not clearly demonstrated by this study. Although a trend was noted for increased velocity of movement to decrease the amount of torque developed, there were no statistically significant differences. The mean shape of the $60°s^{-1}$ and $90°s^{-1}$ curves was similar, particularly when converted to %max torque.

Other factors which may have affected the shape of the EFCP include technical factors such as the damp setting and deceleration in the later part of the curve. The relatively high damp setting used was found to be most suitable for reducing the oscillation train in the torque recordings. The extent to which the curve may have been displaced to the right was not analysed in detail. Visual comparison with curves recorded at lower damp settings suggested that this effect was minimal. Deceleration contributes to the fall in torque at the end of the range of motion, particularly in the last approximately 10°. This part of the curve was not included in the comparison of resistance and capability patterns.

Predicted NEFM Resistance Pattern

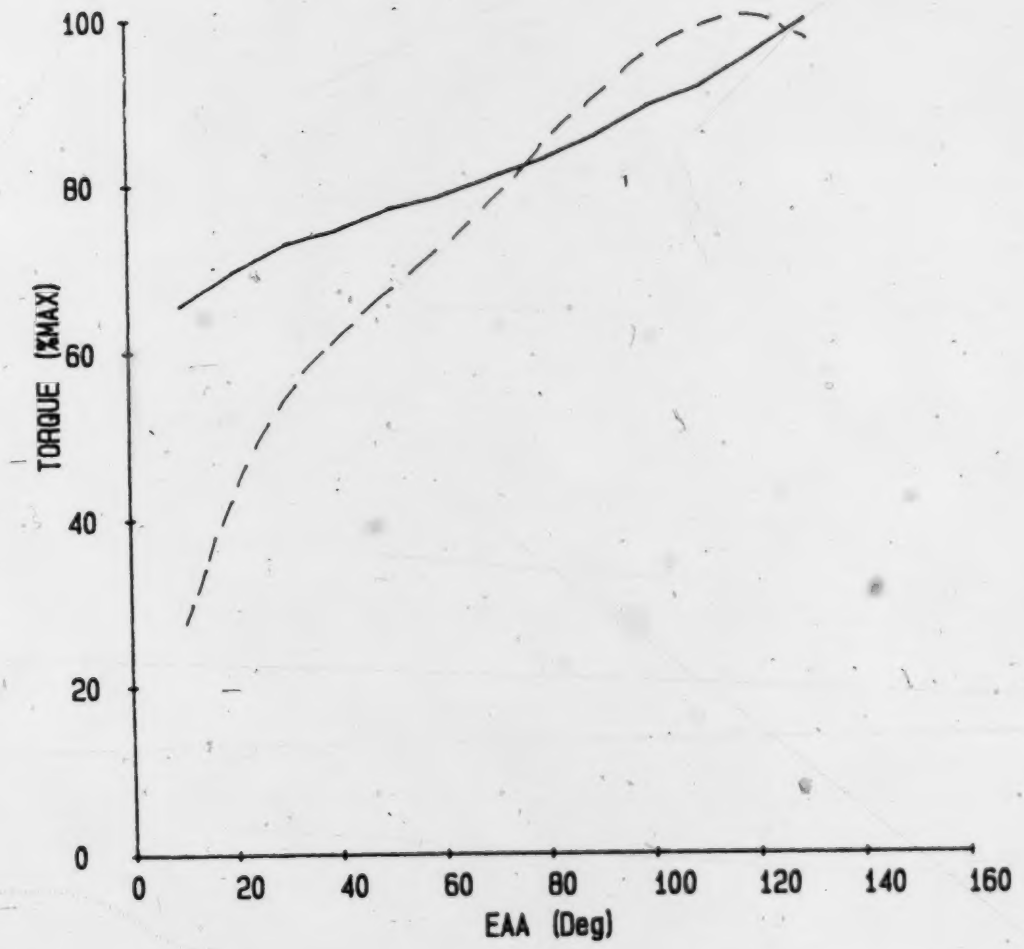
The shape of the predicted NEFM curve was similar regardless of the plate load applied. The primary dependence of the shape of the curve on the values of L_N is consistent with the findings of previous authors.[10,11] The design of the Nautilus cam is such that L_N increases steadily as motion is performed, thus increasing the

effective resistance throughout movement. This is consistent with the described curve of muscle capability according to the Nautilus Company literature,[12] but is not consistent with the derived EFCP (Figure 22). The predicted NEFM resistance pattern had a lesser slope than that of the EFCP over the range of 10° to 130°. The greatest discrepancy between the curves was in the 10° to 50° range where the resistance exceeded capability by 39.71% at 10° and 9.56% at 50°. At the 60° position, the difference between the curves was reduced to 6.02% and remained below 10% throughout the remainder of the range of motion. This suggests that a subject working at a given load would find greater difficulty going through the first part of the range of motion, while the end of the movement would be relatively easier to complete.

The values of sin β and sin α on which the shape of the predicted NEFM resistance pattern also depends, vary in a similar way to L_N. Both increase throughout range except at the 130° point, when sin β falls off in value. The variability in sin β is due to the position of the WA which moves through a fairly wide angle and comes to lie above the horizontal in its final position. Sin α is related to the angle that the chain makes with the WA, this angle being determined both by the position of the WA and the shape of the cam. This angle changes relatively slowly and through a smaller range than β. The ratio of sin β/sin α represents a factor by which L_N is increased. This factor ranges from 0.97 to 1.06 but is generally greater than 1, and serves only slightly to vary the effect of L_N.

Figure 22

Predicted NEFM Resistance Curve and EFCP



Thus, a modification of the nautilus-shaped cam so as to decrease the effect of L_N in the early part of the movement could be sufficient in order to achieve a more adequate match to the EFCP.

Measured NEFM Resistance Patterns

The measurement of the NEFM resistance pattern revealed a series of highly linear curves, of decreasing slope as load was increased. These curves differed from the single predicted curve which was independent of load. The difference in shape of the curves was due mainly to an increase in the initial torque values. This may be explained by inertia effects not taken into account in the analysis. As inertia increases with the weight applied to the WA, so does the torque required to accelerate the load up to the preset velocity.[75] Once the initial inertia is overcome, the effort torque should match the resistance torque more precisely as constant velocity can now be maintained with less force. Inertia effects during the performance of arm curls have been shown to be greatest at fast lifting rates, when the complete range of elbow flexion is completed in less than 2 seconds.[68]

The tendency to increase torque excessively at the beginning of movement may also be related to the subjects perception of the effort required to complete the desired movement against a specified load.[51,52] It may be that muscle function is optimised to achieve the end point of the motion. The initial thrust could represent an overcompensation in the early part of the movement to avoid possible fatigue before the end of the movement is reached. This is a

characteristic that could vary from subject to subject and may be dependent on the relative strength of the individual. The role of such neurological factors is not yet clear and the design of the study does not permit further assessment. Inertial effects may be most significant in explaining the increase in initial torque with increasing load.

Other factors which may have played a less significant role include extraneous electrical noise in the strain record due to the high sensitivity of the system, variability in both the velocity and consistency of lifting technique, and the effect of friction in the system.

Comparison of EFCP and NEFM Resistance Patterns

In order to simplify the quantitative comparison of NEFM and EFCP patterns, the predicted NEFM pattern was compared with the EFCP over the range of 10° to 130° (Figure 22). The predicted pattern was taken to be representative of inherent capabilities of the NEFM, purely due to its design. These are the factors over which the designer has direct control. Since only 130° of movement could be achieved on the NEFM, patterns were compared only over this range.

The lack of similarity between the resistance and capability patterns was consistent with the findings of previous authors who have demonstrated a lack of accurate matching between human torque curves and Nautilus machine resistive torque.[10,11] In the case of the NEFM there were obvious differences in slope and intercept when compared with the EFCP. The slope of the regression curve of the NEFM differed

from than that of the EFCP. While the EFCP changed rapidly and had a fairly sharp rise, the NEFM provided only a slowly changing level of resistance. The greatest mismatch was observed at the 10° position, where resistance torque exceeded capability by as much as 39.71%. This suggested an inherent tendency to significantly overloading the relevant muscle group in the early part of the range of motion with relatively less load being experienced in the latter part of the range. Inspection of the measured NEFM curves suggested that effort torque in the early ranges was increased even more as weights on the WA increased. Overall, the tendency, both inherently and by increasing the external load is to maximise performance in the early part of the movement and to minimize performance at the end of range of motion.

Clinical Implications

The clinical usefulness of the NEFM lies in its applicability to some specific task. As the upper limits of strength are essentially unknown, the EFCP must be seen as being representative of the normal or average biomechanical situation[93] rather than as a curve of absolute maximum capability. This pattern of strength capability is developed in response to the normal tasks of everyday living.

Comparison of the predicted NEFM resistance pattern with the EFCP suggests that training on the NEFM may result in a relative overtraining of the 10° to 50° range of motion, and undertraining of the latter part of the movement. This is inconsistent with the pattern of strength required for the majority of daily living tasks. It is possible that the NEFM resistance pattern may be suited to the

performance of other tasks though these have not been clearly described.

Comparison of the measured and predicted NEFM resistance patterns reveals the difficulty of controlling the pattern of resistance experienced under performance conditions. Strength performance involves a complex interaction of biomechanical, psychological and neurological factors that are yet to be analysed in detail. Thus, even with a set pattern of resistance, it is not yet clear exactly what adaptation will occur. This is definitely an area where further research is needed before conclusive remarks can be made concerning the absolute usefulness of the NEFM in a rehabilitation or physical training setting.

CHAPTER VI

CONCLUSIONS

In relation to the major objectives of the study, the following conclusions were made:

1. The EFCP measured under conditions of constant velocity and in the standard position for use of the NEFM, is an ascending-descending curve over the range of motion of 10° to 150°.

2. The NEFM curve based on a simple mathematical model of the machine under conditions of constant velocity movement, is a linear curve best described by the equation

$$y = 63.6 + 0.262\ x$$

3. The NEFM curve based on a single subject's performance on the machine, and measured by a system of strain gauges, is a series of linear curves of decreasing slope as the weight on the WA is increased.

4. There is a less than ideal match between the EFCP of females and NEFM resistance pattern.

5. The most important factors that vary throughout the range of motion available on the NEFM are L_N, sin β and sin α . These do not vary in such a way as to produce the desired curve, but could be modified in part, or all together, to yield a satisfactory match.

These points of interest were also noted:

6. No mechanical basis could be established for the suggested superiority of the NEFM over more traditional equipment, when this was based on ideal matching of resistance with capability patterns.

7. The complex nature of strength performance, in terms of the neural and psychological factors which modify strength, suggest that it

would be extremely difficult to design a machine to specifically match an individual's strength curve.

Recommendations

The main recommendation arising from the current study is that the shape of the NEFM cam be significantly modified to achieve more accurate matching of the resistance pattern of the machine with the capability pattern for elbow flexion of normal human females.

The findings of the study also warrant the following suggestions:

1. Additional studies are needed to evaluate the inherent resistance patterns of other pieces of Nautilus equipment and to compare these patterns with human capability curves.
2. Comparisons of machine resistance curves should be made only with capability curves derived in the standard positions and using the recommended techniques associated with the particular piece of equipment.
3. Individual patterns of performance on Nautilus equipment should also be analysed to determine the extent to which design dictates performance.
4. Long term studies are needed to investigate the belief that the matching of strength curves leads to specifically altered patterns of strength performance.

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APPENDIX A

INFORMED CONSENT FORMS

Department of Physical Therapy
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INFORMED CONSENT FORM FOR INVESTIGATIVE STUDY

Comparative Analysis of Human Elbow Flexion Capability and Nautilus Elbow Flexion Machine Resistance Patterns

Outline of Procedures (retained by subjects)

A number of exercise machines have been and are continuing to be introduced on the strength training market by various companies. One such company markets a machine which it claims to be superior over traditional training equipment, e.g., barbells, because of the accurate matching of the machine's pattern of resistance with a muscle group's pattern of functioning. This study will determine how well the two patterns do in fact match when elbow flexion/bicep curls are performed.

The part of the study in which you are being asked to participate is in determining the pattern of functioning of the muscles that bend the elbow. The maximum bending effect or moment that can be developed during a biceps curl will be measured.

For the actual testing, you will be asked to perform three (3) maximum effort contractions on a machine that will control your speed of movement. Each maximum contraction will take about 2 secs. and be followed by a rest period of one (1) minute. Prior to the maximum contractions you will be allowed two (2) submaximal effort contractions as a warmup. Each of the submaximal efforts will be followed by a 30 sec. rest period. This procedure will be performed at two (2) speeds of movement. You will be asked to select the order - 'slow' or 'fast' first - in which you prefer to do the exercises. Before the actual

testing you will receive a more detailed explanation of how the machine actually works and be given some time to get familiar with the experimental setup.

The entire test will require no more than about 20 minutes of your time. The only possible risk is of some muscular soreness as you might have experienced following moderate exercise. This soreness is only temporary and should disappear within 2-3 days.

No records which will permit your identification will be made public. Strict confidentiality will be maintained by assigning you a number under which title all your data will be recorded.

You will feel free to withdraw from participation in the study at any time.

If you have any questions concerning the study please feel free to contact Linda Robinson-Edwin, principal investigator at 487-6610 or 432-2068.

Department of Physical Therapy
Faculty of Rehabilitation Medicine
University of Alberta
Edmonton, Alberta

INFORMED CONSENT FORM FOR INVESTIGATIVE STUDY

Comparative Analysis of Human Elbow Flexion Capability and Nautilus Elbow Flexion Machine Resistance Patterns

Subject Consent (retained by investigator)

I, _____, do hereby agree to participate as a subject in the study entitled "Comparative Analysis of Human Elbow Flexion Capability and Nautilus Elbow Flexion Machine Resistance Patterns" to be conducted by Linda Robinson-Edwin. The nature of this study has been explained to me and I understand the risks/ benefits involved. I have been advised that I may withdraw from participation at any time.

_____ _____
(Subject's signature) (Date)

_____ _____
(Address) (Phone no.)

I was a witness during the explanation referred to above and to the signature.

_____ _____
(Witness' signature) (Date)

APPENDIX B

SUBJECTS' ANTHROPOMETRIC DATA

RAW ANTHROPOMETRIC DATA

No.	Age (yrs)	Sex	Height (cm)	Weight (kg)	FL (cm)	HL (cm)	FHL (cm)
01	25	F	155.2	63.5	25.1	17.2	41.7
02	22	F	164.1	76.3	24.7	18.3	42.0
03	21	F	170.3	65.2	24.6	18.8	42.2
04	24	F	161.3	51.5	23.9	17.3	40.3
05	24	F	178.1	67.5	27.6	19.8	45.5
06	22	F	164.6	62.7	24.1	17.1	40.4
07	29	F	161.7	70.2	24.3	17.6	41.4
08	20	F	171.2	60.5	25.3	17.9	42.2
09	20	F	152.2	43.9	21.9	15.7	37.0
10	19	F	167.6	66.9	25.1	18.2	42.8
11	19	F	167.0	66.3	24.3	17.8	40.7
12	22	F	160.3	72.1	23.6	16.8	39.3
13	22	F	170.9	58.1	24.8	18.2	42.3
14	21	F	169.0	61.2	24.2	18.2	42.4
15	22	F	168.3	68.9	25.4	17.5	42.5
16	23	F	152.8	47.2	20.8	16.5	36.4
17	22	F	160.0	54.2	22.6	16.9	39.0
18	27	F	166.7	61.0	23.2	17.1	39.8
19	23	F	159.0	63.2	23.4	17.0	39.4
20	21	F	166.8	58.0	25.1	17.6	42.2
21	28	F	167.4	56.3	25.6	18.0	42.6
22	23	F	165.1	55.8	24.9	17.4	41.7
23	22	F	156.4	40.0	23.5	15.6	38.5
24	29	F	162.9	52.2	24.3	18.1	41.6
25	27	F	164.6	51.1	25.3	17.6	42.6

Note: FL = forearm length; HL = hand length; FHL = length of entire forearm and hand.

SUMMARY ANTHROPOMETRIC DATA

		Females	
Age (Years)	Mean	23.1	
Age	SD	2.9	
Age	Range	19.0	29.0
Wt (kg.)	Mean	59.8	
Wt	SD	8.9	
Wt	Range	40.0	76.3
Ht (cm.)	Mean	164.1	
Ht	SD	6.1	
Ht	Range	152.2	178.1
FL (cm.)	Mean	24.3	
FL	SD	1.3	
FL	Range	20.8	27.6
HL (cm.)	Mean	17.5	
HL	SD	0.9	
HL	Range	15.6	19.8
FHL (cm.)	Mean	41.1	
FHL	SD	2.0	
FHL	Range	36.4	45.5

APPENDIX C

ANTHROPOMETRIC MEASUREMENT TECHNIQUES

Measurement of Height

The subject, wearing light clothing, stood comfortably with feet about 1 inch (1") apart. The subject took a deep breath in, let it out completely and then took in half a full breath. This was held until the height measurement was taken. The axis of the subject's vision was horizontal, eyes looking straight ahead. A rule was applied directly to the top of the skull with minimal pressure. Results were read and entered to the nearest 0.1 cm. The test-retest reliability, r = 0.999.

Measurement of Weight

The subject was first asked to empty her bladder. Dressed in light clothing, the subject stood on the platform of the weighing scale with weight evenly distributed over both feet. The weight measurement was read to the nearest 0.1 kg. The test-retest reliability, $r = 0.999$.

Measurement of Forearm, Hands and Forearm-hand Lengths

The subject lay supine on a plinth with head oriented in the Frankfort plane. The left upper limb was externally rotated at the shoulder with forearm supinated and fingers extended to lie flat on the plinth.

Forearm Length

Using a sliding caliper, the distance along the long axis of the forearm, from the upper margin of the radius (radicle) to the most distal point on the radial styloid (stylion) was measured. The measurement was read and entered to the nearest 0.1 cm. The test-retest reliability, r = 0.945.

Hand Length

With the sliding caliper parallel to the forearm-hand axis, the distance between stylion and the most distal point of the third digit (dactylion III) was measured. The measurement was read and entered to the nearest 0.1 cm. The test-retest reliability, r = 0.947.

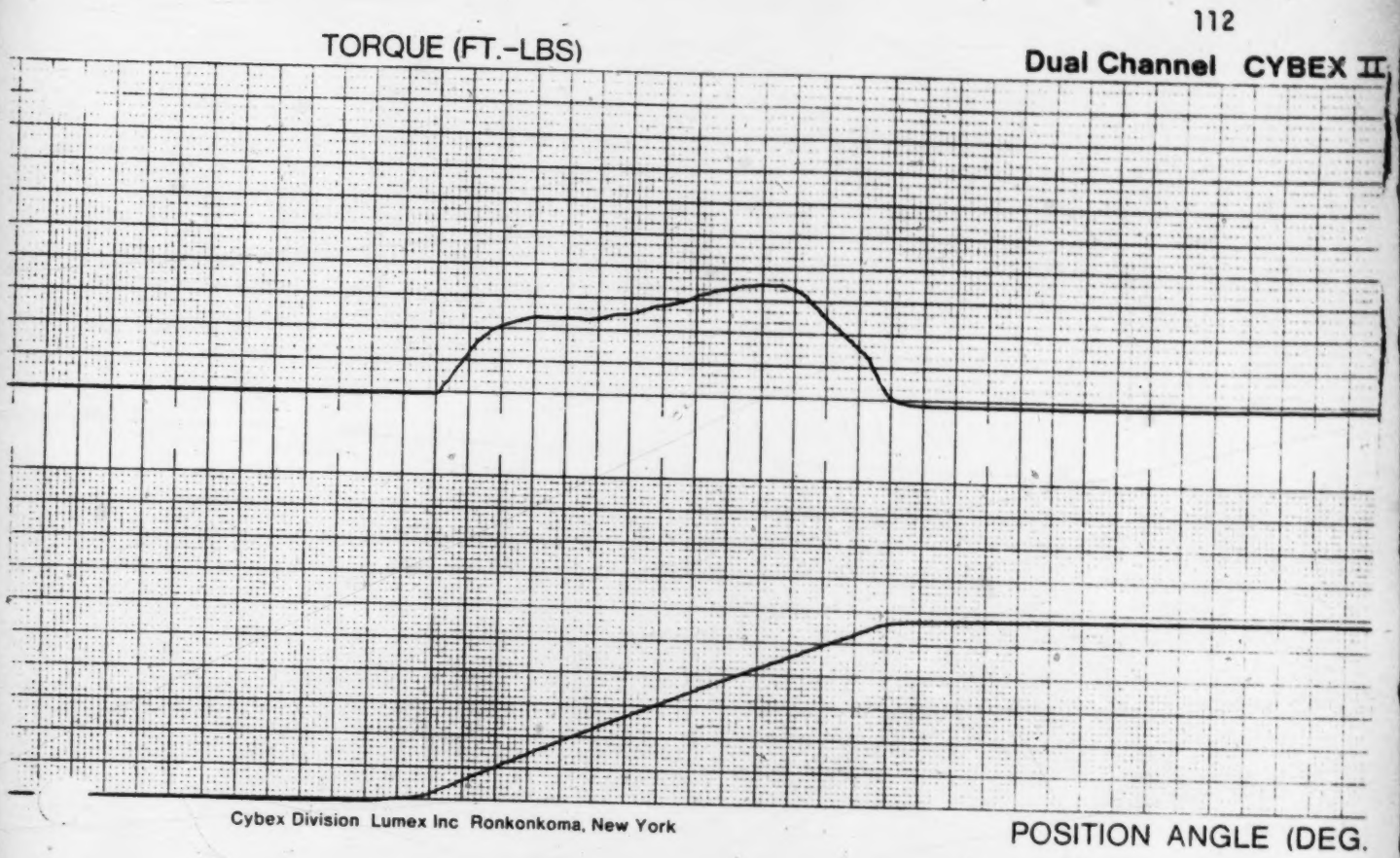
Forearm-hand Length

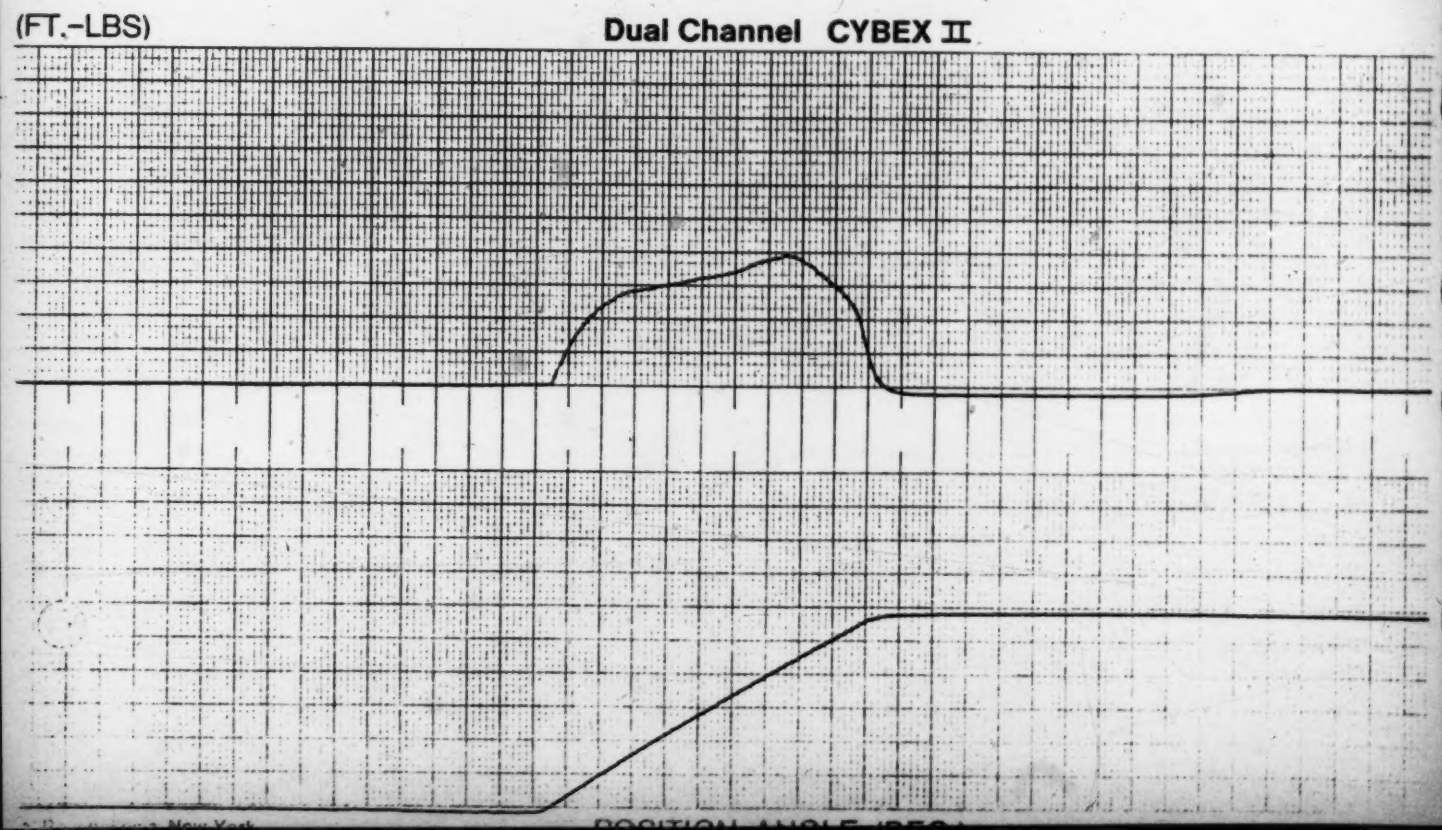
Again with the sliding caliper parallel to the forearm-hand axis, the distance between radiale and dactylion III was measured. The measurement was read and entered to the nearest 0.1 cm. The test-retest reliability, r = 0.994.

APPENDIX D

CYBEX DATA TRACE AND RAW DATA

- RANGE OF MOTION AND ISOKINETIC TORQUE


TORQUE (FT.-LBS)
Dual Channel CYBEX II
Cybex Division Lumex Inc Ronkonkoma, New York
POSITION ANGLE (DEG.


(FT.-LBS)
Dual Channel CYBEX II

MAXIMUM RANGE OF MOTION (°) [at constant velocity to nearest 3°]

	60° sec^{-1}			90° sec^{-1}		
No.	T1	T2	T3	T1	T2	T3
01	189	192	198	180	180	183
02	186	180	186	180	168	180
03	156	162	156	150	150	150
04	171	177	174	174	174	180
05	180	186	180	180	183	180
06	162	159	162	162	162	162
07	168	171	171	174	174	171
08	174	177	180	177	174	177
09	168	171	171	168	168	162
10	189	192	186	186	186	186
11	201	198	198	192	192	195
12	177	177	168	180	180	177
13	177	177	174	171	177	168
14	177	177	180	168	174	177
15	180	180	180	172	183	174
16	168	162	168	156	150	156
17	153	156	165	156	156	156
18	180	180	180	180	180	180
19	174	172	180	168	168	174
20	168	168	171	168	168	165
21	162	162	165	162	159	162
22	156	165	162	168	168	165
23	177	180	177	174	174	171
24	168	168	168	162	174	168
25	177	174	174	162	159	168
$\bar{X}$ =	173.52	174.52	174.96	170.80	171.24	171.48
s =	11.25	10.62	10.31	9.99	10.81	10.45
X_{min} =	153	156	156	150	150	150
X_{max} =	201	198	198	192	192	195

ISOKINETIC TORQUE ($60°s^{-1}$)

SPEED: $60°s^{-1}$		10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°
No.	Trial															
01	1	7.5	12	15	18	16.5	16.5	18	19	24	27	30	31.5	33	36	36
	2	6	10.5	15	16.5	18	18	18	19.5	21	25.5	28.5	31.5	36	39	39
	3	4.5	15	19.5	21	21	19.5	19.5	21	22.5	27	30	33	36	37.5	39
02	1	13.5	21	22.5	22.5	24	25.5	27	28.5	31.5	36	37.5	43.5	45	46.5	45
	2	16.5	24	25.5	27	27	27	30	33	36	36	37.5	39	40.5	42	36
	3	10.5	21	24	25.5	27	27	27	28.5	30	33	36	39	40.5	43.5	46.5
03	1	13.5	18	19.5	21	24	27	30	34.5	37.5	39	39	37.5	31.5	18	1.5
	2	9	13.5	16.5	19.5	22.5	25.5	30	33	36	37.5	36	31.5	24	13.5	1.5
	3	12	16.5	18	19.5	24	27	31.5	36	39	40.5	39	34.5	28.5	22.5	9
04	1	6	13.5	16.5	18	21	24	25.5	28.5	33	34.5	36	31.5	27	24	21
	2	7.5	12	15	19.5	24	25.5	28.5	33	36	39	36	30	28.5	28.5	24
	3	6	13.5	16.5	19.5	24	27	28.5	31.5	33	34.5	36	34.5	31.5	27	24
05	1	7.5	18	24	27	27	30	31.5	33	33	36	37.5	42	42	39	36
	2	7.5	19.5	22.5	25.5	25.5	27	30	31.5	31.5	33	36	39	37.5	37.5	34.5
	3	15	22.5	24	24	25.5	27	28.5	30	33	36	39	42	43.5	42	37.5

ISOKINETIC TORQUE ($60°s^{-1}$) (Continued)

SPEED: $60°s^{-1}$		10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°
No.	Trial															
06	1	19.5	27	30	33	36	39	40.5	42	43.5	42	42	40.5	37.5	34.5	27
	2	19.5	28.5	31.5	33	36	39	39	40.5	40.5	40.5	39	39	36	30	21
	3	10.5	22.5	30	33	36	37.5	39	40.5	42	42	40.5	40.5	37.5	30	21
07	1	16.5	27	31.5	34.5	34.5	35	39	42	42	42	39	39	37.5	31.5	25.5
	2	12	25.5	31.5	33	36	35	37.5	36	37.5	37.5	39	40.5	40.5	36	30
	3	15	24	30	33	36	35	35	34.5	33	33	36	35	35	34.5	30
08	1	12	19.5	22.5	24	28.5	33	36	39	42	43.5	43.5	45	43.5	43.5	43.5
	2	15	21	22.5	24	27	31.5	36	42	42	45	48	48	48	49.5	51
	3	15	21	22.5	25.5	27	30	34.5	39	42	45	45	46.5	48	48	48
09	1	6	12	16.5	21	24	24	24	25.5	25.5	24	24	22.5	22.5	18	15
	2	7.5	18	22.5	24	27	27	28.5	30	30	31.5	33	31.5	25.5	25.5	24
	3	6	12	16.5	19.5	21	22.5	24	25.5	25.5	24	22.5	21	19.5	19.5	18
10	1	12	18	21	24	27	30	31.5	34.5	36	40.5	43.5	45	51	49.5	46
	2	13.5	19.5	21	24	27	30	33	37.5	39	42	43.5	48	49.5	48	45
	3	12	19.5	22.5	24	27	30	31.5	34.5	36	40.5	42	43.5	45	45	45

ISOKINETIC TORQUE ($60°s^{-1}$) (Continued)

SPEED: $60°s^{-1}$		10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°
No.	Trial															
11	1	3	4.5	4.5	6	7.5	9	12	15	16.5	19.5	22.5	24	27	28.5	27
	2	3	3	3	6	7.5	9	10.5	13.5	15	18	21	24	27	27	27
	3	3	4.5	4.5	6	6	6	7.5	9	12	15	19.5	21	24	27	24
12	1	5.5	8.5	11	11.5	12	12	12.5	13	15	16	18	19	20	20.5	19.5
	2	1.5	5	7.5	8	8	7.5	8	9.5	12.5	15	17.5	18	17	16	13
	3	0.5	4.5	7	8.5	10	10.5	11.5	12	12	13	14	15.5	16	14	10
13	1	6	16.5	22.5	25.5	24	22.5	22.5	27	30	33	27.5	40.5	42	36	28.5
	2	9	18	24	24	15.5	27	30	33	37.5	39	39	39	37.5	33	24
	3	7.5	16.5	19.5	21	24	25.5	27	30	33	33	33	31.5	30	24	16.5
14	1	7.5	15	19.5	21	22.5	24	25.5	28.5	33	36	39	42	42	40.5	36
	2	9	15	18	21	21	22.5	25.5	30	33	36	39	42	43.5	42	37.5
	3	10.5	15	18	19.5	21	24	27	31.5	33	36	36	37.5	39	34.5	31.5
15	1	10.5	15	15	15	18	19.5	21	24	27	28.5	33	34.5	36	36	31.5
	2	4.5	10.5	13.5	15	16.5	18	18	21	24	27	30	33	34.5	33	33
	3	12	15	13.5	15	16.5	18	21	21	24	27	31.5	33	33	33	31.5

ISOKINETIC TORQUE ($60°s^{-1}$) (Continued)

SPEED: $60°s^{-1}$		10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°
No.	Trial															
16	1	9	15	19.5	19.5	21	19.5	19.5	21	22.5	24	25.5	24	21	18	12
	2	6	12	15	15	16.5	16.5	18	19.5	21	22.5	24	22.5	22.5	21	13.5
	3	13.5	18	21	21	21	21	19.5	21	22.5	25.5	24	24	24	19.5	19
17	1	12	15	15	15	13.5	16.5	21	24	27	30	30	28.5	25.5	15	4.5
	2	12	15	15	16.5	18	19.5	22.5	25.5	28.5	30	31.5	30	28.5	21	6
	3	15	18	18	18	18	18	18	21	22.5	25.5	24	24	22.5	18	10.5
18	1	7.5	15	18	21	22.5	24	25.5	27	27	27	27	27	28.5	27	24
	2	10.5	18	21	24	24	24	24	25.5	25.5	24	24	25.5	27	25.5	25.5
	3	12	19.5	22.5	24	25.5	27	25.5	24	21	19.5	21	22.5	24	25.5	27
19	1	15	19.5	21	24	28.5	30	30	31.5	34.5	36	36	34.5	33	30	24
	2	15	18	21	24	27	28.5	30	31.5	36	37.5	37.5	37.5	36	33	28.5
	3	12	16.5	18	19.5	21	24	27	30	31.5	34.5	36	36	33	30	24
20	1	18	22.5	24	22.5	22.5	22.5	24	27	28.5	30	34.5	37.5	36	30	25.5
	2	15	22.5	24	21	21	22.5	24	27	28.5	30	33	33	33	30	24
	3	16.5	21	22.5	21	21	22.5	24	25.5	27	30	33	34.5	34.5	31.5	25.5

ISOKINETIC TORQUE ($60°s^{-1}$) (Continued)

SPEED: $60°s^{-1}$		10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°
No.	Trial															
21	1	10.5	13.5	19.5	22.5	22.5	25.5	25.5	25.5	30	39	42	45	45	43.5	40.5
	2	10.5	18	22.5	24	27	27	28.5	31.5	33	36	37.5	42	43.5	45	39
	3	13.5	19.5	21	24	24	25.5	25.5	25.5	28	30	34.5	39	42	43.5	40.5
22	1	10.5	15	19.5	22.5	27	28.5	28.5	30	30	30	30	28.5	27	24	16.5
	2	10.5	19.5	22.5	25.5	27	30	33	31.5	31.5	33	33	30	27	22.5	15
	3	13.5	19.5	21	24	25.5	27	28.5	30	33	33	33	33	30	24	16.5
23	1	2.5	8	10.5	12.5	14	16.5	17.5	18.5	19.5	18	17.5	15.5	12.5	10.5	8
	2	4	9	12	14.5	17	18.5	21	22	20.5	19	19	19	19.5	19	16
	3	2	6	9.5	12	14.5	15.5	16.5	18	19.5	20.5	18.5	19	18	16.5	13
24	1	2	4	5.5	6.5	8	9.5	11.5	14	16	17.5	19	20	20	18	13.5
	2	3	6.5	8	9	9	10	11.5	13	15	16	17	18	17	15	10.5
	3	2.5	5	6	8	9	10.5	11	12.5	14.5	16.5	18.5	19.5	19	16.5	13.5
25	1	5	8.5	12.5	15	16.5	18	19.5	21.5	24.5	27	27	25.5	22.5	19	15
	2	0.5	7	11.5	13.5	14.5	16.5	18.5	22	25	26	25.5	21.5	16.5	14	10.5
	3	4.5	7	9.5	12	13.5	16	18	19.5	22	23	23	22	18	13	10

ISOKINETIC TORQUE ($90°s^{-1}$)

SPEED: $90°s^{-1}$		10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°
No.	Trial															
01	1	6	10.5	16.5	21	22.5	24	25.5	27	28.5	28.5	30	30	30	30	28.5
	2	9	15	19.5	22.5	24	27	28.5	28.5	30	31.5	31.5	33	33	33	28.5
	3	3	10.5	15	19.5	22.5	24	27	28.5	28.5	31.5	31.5	33	31.5	28.5	22.5
02	1	9	30	34.5	37.5	39	39	34.5	36	36	33	31.5	34.5	39	45	48
	2	9	21	28.5	31.5	33	33	31.5	30	28.5	28.5	28.5	30	31.5	27	18
	3	9	22.5	30	31.5	30	31.5	31.5	33	31.5	31.5	33	33	34.5	37.5	36
03	1	7.5	12	15	18	21	24	30	33	36	34.5	31.5	27	18	10.5	3
	2	6	12	15	18	21	24	27	31.5	33	36	36	30	19.5	9	1.5
	3	7.5	12	15	18	21	24	28.5	33	34.5	36	33	28.5	18	7.5	1.5
04	1	3	9	12	16.5	19.5	21	22.5	25.5	27	28.5	30	30	28.5	24	22.5
	2	6	12	15	18	21	22.5	24	27	30	31.5	33	33	31.5	28.5	22.5
	3	4.5	10.5	15	17	21	21	24	27	28.5	31.5	31.5	30	27	24	21
05	1	10.5	15	21	24	25.5	25.5	27	28.5	30	33	36	36	37.5	34.5	31.5
	2	7.5	15	19.5	24	27	28.5	28.5	30	33	36	37.5	39	37.5	33	30
	3	6	15	21	24	27	27	28.5	30	33	36	37.5	37.5	36	33	30

ISOKINETIC TORQUE ($90°s^{-1}$) (Continued)

SPEED: $90°s^{-1}$		10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°
No.	Trial															
06	1	12	22.5	27	30	33	33	34.5	36	36	39	42	42	39	33	19.5
	2	13.5	22.5	27	27	28.5	31.5	34.5	37.5	39	39	37.5	34.5	31.5	21	10.5
	3	13.5	22.5	28.5	31.5	33	36	39	42	45	45	42	39	34.5	27	16.5
07	1	15	21	24	24	22.5	22.5	24	24	25.5	28.5	31.5	33	36	36	31.5
	2	6	12	16.5	19.5	22.5	24	24	25.5	27	30	34.5	40.5	42	42	37.5
	3	6	15	19.5	24	25.5	28.5	31.5	33	37.5	40.5	43.5	45	45	42	34.5
08	1	9	16.5	22.5	24	25.5	27	30	33	36	39	42	43.5	43.5	42	37.5
	2	9	16.5	19.5	22.5	25.5	27	31.5	34.5	36	37.5	40.5	43.5	45	46.5	45
	3	10.5	18	21	24	27	30	33	36	37.5	39	40.5	43.5	48	51	48
09	1	7.5	16.5	21	22.5	22.5	24	25.5	25.5	25.5	25.5	27	27	27	28.5	27
	2	4.5	12	18	21	22.5	24	22.5	22.5	22.5	21	21	19.5	16.5	15	10.5
	3	6	12	19.5	22.5	24	25.5	24	22.5	21	18	16.5	15	13.5	12	9
10	1	9	16.5	21	22.5	27	30	33	36	39	42	45	45	48	48	43.5
	2	9	18	24	27	27	30	33	34.5	37.5	42	45	45	45	45	43.5
	3	10.5	19.5	22.5	24	25.5	28.5	33	36	39	40.5	43.5	45	46.5	46.5	42

ISOKINETIC TORQUE ($90°s^{-1}$) (Continued)

SPEED: $90°s^{-1}$		10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°
No.	Trial															
11	1	1.5	3	4.5	6	7.5	9	13.5	15	18	21	22.5	27	28.5	31.5	31.5
	2	3	4.5	4.5	6	6	9	10.5	13.5	16.5	18	21	24	25.5	27	22.5
	3	1.5	1.5	3	4.5	6	7.5	10.5	13.5	18	21	24	27	28.5	30	28.5
12	1	0.5	3	4	6	8.5	11	13	14.5	16	18	20	21	22.5	18.5	15
	2	3	6	6.5	8	9	11	12.5	13.5	14	14	15	15	13	11	8
	3	1	2.5	4	5	6	8.5	11	12.5	13.5	15	15	14	12	10.5	7
13	1	3	6	15	19.5	22.5	25.5	28.5	31.5	33	34.5	33	33	28.5	24	18
	2	3	9	15	21	24	25.5	28.5	33	34.5	36	36	34.5	31.5	25.5	19.5
	3	4.5	10.5	16.5	21	24	27	30	33	34.5	36	33	31.5	27	21	13.5
14	1	7.5	13.5	16.5	21	22.5	24	25.5	28.5	30	34.5	36	39	39	34.5	24
	2	9	13.5	18	22.5	24	24	28.5	30	33	36	37.5	39	42	39	33
	3	7.5	13.5	19.5	21	24	27	30	33	34.5	36	37.5	37.5	36	34.5	30
15	1	6	10.5	10.5	12	15	18	21	22.5	24	27	28.5	30	28.5	25.5	19.5
	2	6	9	10.5	12	16.5	18	21	25.5	27	30	31.5	33	34.5	33	28.5
	3	4.5	7.5	9	12	15	18	21	22.5	25.5	28.5	31.5	34.5	34.5	31.5	22.5

ISOKINETIC TORQUE ($90°s^{-1}$) (Continued)

SPEED: $90°s^{-1}$		10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°
No.	Trial															
16	1	10.5	15	16.5	18	18	18	19.5	21	21	22.5	22.5	21	19.5	15	1.5
	2	7.5	12	13.5	15	16.5	18	19.5	21	22.5	24	24	21	16.5	10.5	1.5
	3	4.5	6	7.5	10.5	12	12	13.5	15	16.5	19.5	21	19.5	16.5	13.5	6
17	1	9	13.5	15	18	18	19.5	19.5	21	24	25.5	27	27	25.5	16.5	3
	2	3	7.5	12	12	13.5	15	18	21	22.5	25.5	27	28.5	27	18	6
	3	7.5	9	10.5	12	12	13.5	18	21	24	27	27	27	24	13.5	4.5
18	1	7.5	15	18	21	22.5	22.5	22.5	21	21	19.5	19.5	22.5	24	24	24
	2	4.5	10.5	15	18	19.5	21	22.5	22.5	24	24	25.5	27	27	27	27
	3	6	9	13.5	15	18	19.5	19.5	21	21	22.5	24	25.5	27	28.5	28.5
19	1	9	13.5	16.5	19.5	22.5	24	28.5	31.5	33	34.5	34.5	31.5	28.5	22.5	15
	2	6	12	15	18	21	22.5	24	28.5	31.5	31.5	31.5	30	25.5	21	13.5
	3	12	13.5	16.5	18.0	19.5	21	24	28.5	30	31.5	30	28.5	27	22.5	13.5
20	1	10.5	16.5	18	19.5	21	22.5	25.5	30	31.5	33	33	33	31.5	28.5	27
	2	12	18	19.5	21	24	25.5	27	30	31.5	31.5	31.5	30	30	27	28.5
	3	9	16.5	19.5	21	21	22.5	24	27	28.5	30	31.5	33	33	30	27

ISOKINETIC TORQUE ($90°s^{-1}$) (Continued)

SPEED: $90°s^{-1}$		10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°
No.	Trial															
21	1	10.5	18	21	24	25.5	25.5	27	28.5	33	36	37.5	39	43.5	42	34.5
	2	9	15	19.5	21	21	19.5	21	24	27	30	33	39	42	42	31.5
	3	6	15	18	21	21	21	21	22.5	25.5	27	33	36	37.5	39	24
22	1	4.5	10.5	15	18	21	24	27	28.5	31.5	33	31.5	30	27	22.5	16.5
	2	7.5	15	18	21	24	27	27	28.5	30	31.5	30	28.5	27	24	15
	3	7.5	15	21	24	25.5	27	28.5	30	30	31.5	30	28.5	25.5	21	13.5
23	1	3.5	5.5	7.5	10	13.5	15.5	17.5	19	21	22	21.5	20	19.5	17.5	14.5
	2	3	6	8.5	11	13.5	15.5	18.5	19	20	20	19.5	17.5	15.5	13.5	11.5
	3	3	7	9.5	12	13.5	15	17	19	20	20.5	19.5	18	16	13.5	10
24	1	0.5	2.5	4.5	6.5	8	10	12.5	14	15.5	16.5	16.5	16.5	14.5	10.5	1.5
	2	0	1.5	3.5	5.5	7	8.5	9	10.5	12	12.5	13	12.5	10	5.5	2.5
	3	0	1.5	3.5	5.5	7	8.5	10	11.5	13.	16	17	16.5	14.5	10	6
25	1	0	4	5.5	7	8	11	12.5	14.5	13.5	11.5	9.5	7	3.5	1.5	0
	2	1.5	5	6.5	9	11	12.5	13.5	14.5	15	13	11	7.5	5	1.5	0
	3	3	6.5	8.5	10	11	13	15	16.5	18.5	19	18	15.5	13	7	3

APPENDIX E

NEFM MEASUREMENTS AND CALCULATED VALUES

MEASUREMENT AND RELIABILITY OF α

EAA (°)	T_1	T_2	$\bar{T}_\alpha$
10	49.0	49.0	49.0
20	51.0	51.0	51.0
30	53.0	53.0	53.0
40	55.0	54.0	54.5
50	56.0	56.0	56.0
60	58.0	58.0	58.0
70	60.0	60.0	60.0
80	62.0	62.0	62.0
90	64.0	64.0	64.0
100	66.0	66.0	66.0
110	68.0	68.0	68.0
120	90.0	70.0	69.5
130	71.0	71.0	71.0

Coefficient of reliability, r = 0.9987.

MEASUREMENT AND RELIABILITY OF B

EAA (°)	T_1	T_2	$\overline{T}_B$
10	47.0	47.0	47.0
20	52.0	52.0	52.0
30	56.0	58.0	57.0
40	60.0	60.0	60.0
50	64.0	64.0	64.0
60	67.0	69.0	68.0
70	71.0	73.0	72.0
80	76.0	76.0	76.0
90	80.0	80.0	80.0
100	84.0	84.0	84.0
110	87.0	89.0	88.0
120	92.0	94.0	93.0
130	97.0	95.0	96.0

Coefficient of reliability, r = 0.997.

MEASUREMENT AND REPRODUCIBILITY OF NEFM DIMENSIONS

Dimension	Units	Reproducibility	Value
W_{WA}	kg.	.0005	4.27
A_W	cm.	.05	71.77
A_{WA}	cm.	.10	43.72
A_F	cm.	.06	51.75

MEASUREMENT AND RELIABILITY OF L_N

EAA (°)	T_1	T_2	$\overline{X}_{L_N}$
0	16.9	16.8	16.85
10	17.2	17.1	17.15
20	17.5	17.3	17.40
30	17.7	17.5	17.60
40	17.9	17.9	17.90
50	18.1	18.0	18.05
60	18.2	18.3	18.25
70	18.6	18.8	18.70
80	19.1	19.3	19.20
90	19.7	20.1	19.90
100	20.7	21.0	20.85
110	21.5	21.7	21.60
120	22.6	22.8	22.70
130	24.1	24.1	24.10

Coefficient of reliability, r = 0.997.

APPENDIX F

NEFM RAW DATA - STRAIN AND VELOCITY

NEFM STRAIN (arbitrary units)

W(kg) EAA (°)	4.54		6.80		9.07		11.34		13.61		15.88		18.14	
	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2
10	8.5	8.5	11	11	15	15	19	19.5	23	23	28	26.5	33	32
20	9	9	12	12	15.5	15.5	20	20	24	24	29	28	33.5	34.5
30	9.5	9.5	12.5	13	16.5	16.5	21	21	25	26	29	29	34	33.5
40	9.5	9.5	13.5	13	16.5	17	21.5	21	26	26	31	29	35	35.5
50	10	10	14	13.5	17	17	22	21.5	26.5	26.5	31	31	35	36
60	10.5	11	14.5	14	18	17.5	22	23	27	27	31	31.5	37	36
70	11.5	11.5	14.5	14.5	18.5	18.5	24	23.5	27	28	30	31	37	37
80	11.5	11.5	15	15	19	19	23.5	24	28	29	33	32	37	37
90	12	12	15.5	15	19.5	20	24	24	29	29	33	33.5	38.5	38
100	12.5	13	16	16	20	20.5	25.5	25.5	30	30	34	34	40	40
110	12.5	13	16	16.5	21	21	25.5	26	30	31	35	35	40	42
120	13	13	16	16.5	21	20	26	25	30.5	30.5	33.5	34.5	39.5	40.5
130	12.5	13	16	16	21	21	26	26	30.5	30	35	35	42	41

NEFM STRAIN (%max)

W(kg)	4.54		6.80		9.07		11.34		13.61		15.88		18.14		Coeff. of linearity r
EAA (°)	X	% max	X	% max	X	% max	X	% max	X	% max	X	% max	X	% max	
10	8.50	65.38	11.00	67.69	15.00	71.43	19.25	74.04	23.00	75.41	27.25	77.86	32.50	78.31	0.997
20	9.00	69.23	12.00	73.85	15.50	73.81	20.00	76.92	24.00	78.69	28.50	81.43	34.00	81.93	0.996
30	9.50	73.08	12.75	78.46	16.50	78.57	21.00	80.77	25.50	83.61	29.00	82.86	33.75	81.33	0.999
40	9.50	73.08	13.25	81.54	16.75	79.76	21.25	81.73	26.00	85.25	30.00	85.71	35.25	84.94	0.998
50	10.00	76.92	13.75	84.62	17.00	80.95	21.75	83.65	26.50	86.89	31.00	88.57	35.50	85.54	0.998
60	10.75	82.69	14.25	87.69	17.75	84.52	22.50	86.54	27.00	88.52	31.25	89.29	36.50	87.95	0.998
70	11.50	88.46	14.50	89.23	18.50	88.10	23.75	91.35	27.50	90.16	30.50	87.14	37.00	89.16	0.996
80	11.50	88.46	15.00	92.31	19.00	90.48	23.75	91.35	28.50	93.44	32.50	92.86	37.00	89.16	0.999
90	12.00	92.31	15.25	93.85	19.75	94.05	24.00	92.31	29.00	95.08	33.25	95.00	38.25	92.17	0.999
100	12.75	98.08	16.00	98.46	20.25	96.43	25.50	98.08	30.00	98.36	34.00	97.14	40.00	96.39	0.998
110	12.75	98.08	16.25	100.00	21.00	100.00	25.75	99.04	30.50	100.00	35.00	100.00	41.00	98.80	0.998
120	13.00	100.00	16.25	100.00	20.50	97.62	25.50	98.08	30.50	100.00	34.00	97.14	40.00	96.39	0.998
130	12.75	98.08	16.00	98.46	21.00	100.00	26.00	100.00	30.25	99.18	35.00	100.00	41.50	100.00	0.997

NEFM VELOCITY DATA

W(kg)	4.54		6.80		9.07		11.34		13.61		15.88		18.14	
Trial	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2
Range (°)	Distances on chart (mm.)													
10-20	7.0	5.5	5.5	6.0	5.5	4.0	5.0	5.0	4.0	5.5	6.0	6.5	6.0	5.5
20-30	4.0	4.5	4.5	4.0	4.5	4.5	5.0	4.0	4.5	4.5	4.5	5.0	5.0	4.0
30-40	3.0	4.0	5.0	3.5	3.0	3.5	4.0	3.0	3.5	3.5	4.5	3.0	3.5	4.5
40-50	3.5	2.5	4.5	3.0	3.0	3.0	4.0	3.0	3.0	2.5	3.0	4.0	4.5	4.0
50-60	3.5	3.5	4.5	3.0	4.0	3.0	3.0	4.0	3.5	3.0	3.0	3.0	4.5	5.0
60-70	3.5	3.5	3.5	3.0	3.0	3.0	3.0	1.5	1.5	3.0	3.0	2.0	3.5	4.0
70-80	3.0	3.0	3.5	4.0	4.0	5.0	3.0	3.5	4.0	4.0	4.0	2.0	4.0	4.5
80-90	5.5	6.5	6.0	5.0	6.0	5.5	3.5	5.0	5.5	6.0	5.0	4.5	5.0	5.5
90-100	5.5	9.0	6.0	6.0	7.0	5.5	6.5	7.0	6.5	7.0	5.0	4.0	5.0	6.0
100-110	6.0	7.0	6.0	8.0	8.0	7.5	7.0	6.0	7.5	8.0	5.5	6.5	7.0	7.0
110-120	8.0	7.5	6.0	7.0	7.0	4.5	8.0	5.0	7.0	6.0	4.5	6.0	6.5	5.0
120-130	4.0	5.5	7.0	5.0	8.0	7.0	8.0	8.0	4.5	6.0	8.0	9.0	4.5	8.0
Total distance (mm.)	56.0	62.0	62.0	58.0	63.0	56.0	60.0	55.0	55.0	59.0	56.0	55.5	59.0	64.0
Total time (s) 1 sec. = 10 mm.	5.90		6.00		5.95		5.75		5.70		5.57		6.15	

APPENDIX G

ANOVA SUMMARY TABLES

SUMMARY OF 3-WAY ANALYSIS OF VARIANCE

A = speed, B = trial, C = angle

Source	SS	DF	MS	F	P
BET SUBJ	110229.00	49			
A	3140.0000	1	3140.0000	1.41	0.241
SUBJ W GROUP	107089.00	48	2231.0208		
WITHIN SUBJ	142216.00	2200			
B	125.00000	2	62.500000	1.75	0.180
AB	90.000000	2	45.000000	1.26	0.289
B X SUBJ W G	3432.0000	96	35.750000		
C	95448.000	14	6817.7109	122.10	0.000
AC	581.00000	14	41.500000	0.74	0.731
C X SUBJ W G	37524.000	672	55.839279		
BC	48.000000	28	1.7142849	0.48	0.990
ABC	172.00000	28	6.1428566	1.72	0.011
BC X SUBJ W G	4796.0000	1344	3.5684519		

SUMMARY OF 1-WAY ANALYSIS OF VARIANCE

Source	SS	DF	MS	F	P
BET SUBJ	6894.5625	12	574.54688		
WITHIN SUBJ	659.37500	78	8.4535255		
REPT MEAS	288.81250	6	48.135406	9.35	0.00000
RESIDUAL	370.56250	72	5.1467009		
TOTAL		90			

NEWMAN-KEULS COMPARISON BETWEEN ORDERED MEANS

Q-values for mean differences

	MEANS	90.385	90.353	89.390	88.758	88.166	87.363	84.911
1	84.911	8.698	8.648	7.117	6.114	5.173	3.896	0.0
3	87.363	4.802	4.752	3.221	2.218	1.276	0.0	
2	88.166	3.526	3.476	1.945	0.941	0.0		
4	88.758	2.585	2.534	1.004	0.0			
7	89.390	1.581	1.531	0.0				
5	90.353	0.050	0.0					